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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/757,150	01/08/2001	Toshiki Tajima	IL-10626	6360

7590 07/17/2003

Christopher J. Horgan
Patent Attorney
L-703
P.O. Box 808
Livermore, CA 94551

EXAMINER
WELLS, NIKITA

ART UNIT	PAPER NUMBER
2881	

DATE MAILED: 07/17/2003

Please find below and/or attached an Office communication concerning this application or proceeding.

Office Action Summary	Application No.	Applicant(s)	
	09/757,150	TAJIMA, TOSHIKI	
	Examiner	Art Unit	
	Nikita Wells	2881	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If the period for reply specified above is less than thirty (30) days, a reply within the statutory minimum of thirty (30) days will be considered timely.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133).
- Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *09 June 2003* .

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) *1-90* is/are pending in the application.

4a) Of the above claim(s) *1-39,43-47,51-65 and 69-87* is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) *40-42,48-50,66-68 and 88-90* is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☒ Claim(s) *40-42,48-50,66-68 and 88-90* are subject to restriction and/or election requirement.

Application Papers

9)☐ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on *08 January 2001* is/are: a)☐ accepted or b)☒ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

11)☐ The proposed drawing correction filed on _____ is: a)☐ approved b)☐ disapproved by the Examiner.

If approved, corrected drawings are required in reply to this Office action.

12)☐ The oath or declaration is objected to by the Examiner.

Priority under 35 U.S.C. §§ 119 and 120

13)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

14)☒ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. § 119(e) (to a provisional application).

a)☐ The translation of the foreign language provisional application has been received.

15)☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. §§ 120 and/or 121.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)
3) ☒ Information Disclosure Statement(s) (PTO-1449) Paper No(s). *1 and 2*
4) ☒ Interview Summary (PTO-413) Paper No(s). _____.
5) ☐ Notice of Informal Patent Application (PTO-152)
6) ☐ Other:

DETAILED ACTION

Claim Rejections - 35 USC § 103

1. The following is a quotation of 35 U.S.C. 103(a) which forms the basis for all obviousness rejections set forth in this Office action:

> (a) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

2. Claims 40-42, 48-50, 66-68, and 88-90, are rejected under 35 U.S.C. 103(a) as being unpatentable over Umstadter et al. (5,789,876) in view of Schultheiss et al. (5,576,593), and further in view of Slatkin et al. (5,339,347) and S.B. Segall (4,215,274).

With respect to claims 40-42 and 48-50, Umstadter et al. disclose (Abstract; Figs. 4 and 17; Col. 1, line 36-42; Col. 10, lines 18-37;) an accelerator comprising: a laser system (200); a target (310) to receive a laser pulse from said laser system (200); and a beam transport system operatively coupled to said target (310). Umstadter et al. also disclose that the transport system is capable of delivering energy of the electron beam up to 3 GeV (see Col. 1, line 36-42) while the Applicant's claim 48 teaches that the transport system has the capacity of delivering energy in the range of approximately 10 to approximately 500 MeV. Umstadter et al. fail to disclose that the target has a first layer and a second layer and that the laser pulse is capable of producing an energy per laser shot of between approximately 1 and 10 Joules. However, Schultheiss et al. disclose that the target has a first layer and a second layer (Col. 6, lines 40-45) and that the laser pulse capable of producing 1 and 10 Joules of energy (Col. 7, lines 8-11).

It would have been obvious to a person of ordinary skill in the art at the time the invention was made to recognize and substitute the apparatus for accelerating charged particles of Schultheiss et al. into the apparatus for generating and accelerating ultra-short electron pulses of Umstadter et al. in order to obtain optimum acceleration of the electrons in a shorter distance thus allowing a much smaller overall apparatus.

With respect to claims 66-68, Umstadter et al. disclose (Abstract; Figs. 4 and 17; Col. 1, line 36-42; Col. 10, lines 18-37) an accelerator comprising: a laser system (200); a target (310) to receive a laser pulse from said laser system (200); and a beam transport system, but fail to disclose that the beam transport system is capable of delivering energy which may penetrate about 10 to about 20 cm beneath the surface of skin tissue in a treatment field, delivering energy to produce a dose per shot at a treatment field in the range of about .1 to about 10 Gy, or a dose per second at a treatment field of approximately .1 to approximately 100 Gy/second. However, Slatkin et al. disclose beam transport system which is capable of delivering energy which may penetrate about 10 to about 20 cm beneath the surface of skin tissue in a treatment field (Col. 7, lines 54-61), delivering energy to produce a dose per shot in the range of .1 to 10 Gy (Col. 2, lines 27-32), or a dose per second of .1 to 100 Gy/second (Col. 2, lines 45-48).

It would have been obvious to a person of ordinary skill in the art at the time the invention was made to recognize and substitute the method for performing radiation therapy on a patient of Slatkin et al. into the apparatus for generating and accelerating ultra-short electron pulses of Umstadter et al. in order to deliver the optimum dose and dose rate at a treatment field in a patient.

With respect to claims 88-90, Slatkin et al. disclose beam transport system which is capable of delivering energy which may penetrate beneath the surface of skin tissue in a treatment, but fail to disclose that the pulse is guided through a fiber optic section to the target in a treatment field. However, S.B. Segall discloses (claim 42; Col. 14, line 57 to Col. 15, line 4; and Col. 19, lines 53-59) the delivery of energy where the pulse is guided through a fiber optic section to the target.

It would have been obvious to a person of ordinary skill in the art at the time the invention was made to recognize and substitute the delivery of energy where the pulse is guided through a fiber optic section to the target of S.B. Segall into the method for performing radiation therapy on a patient of Slatkin et al. in order to deliver the optimum dose and dose rate at a treatment field in a patient.

Conclusion

3. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure. Rentzepis et al. (5,930,331) disclose a compact high-intensity pulsed X-ray source utilizing a pulsed laser to accelerate an electron beam.

4. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Nikita Wells whose telephone number is (703) 305-0416. The examiner can normally be reached 8:30 AM - 5:00 PM.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, John R. Lee can be reached on (703) 308-4116. . The fax phone numbers for the organization where this application or proceeding is assigned are (703) 872-9318 for regular

communications and (703) 872-9319 for After Final communications. Any inquiry of a general nature or relating to the status of this application or proceeding should be directed to the receptionist whose telephone number is (703) 308-0956.

Nikita Wells

Examiner, Art Unit 2881

July 8, 2003

Notice of References Cited	Application/Control No. 09/757,150	Applicant(s)/Patent Under Reexamination TAJIMA, TOSHIKI	
	Examiner Nikita Wells	Art Unit 2881	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-5,789,876	08-1998	Umstadter et al.	315/507
	B	US-5,576,593	11-1996	Schultheiss et al.	313/231.31
	C	US-5,339,347	08-1994	Slatkin et al.	378/65
	D	US-4,215,274	07-1980	Segall, Stephen B.	250/361R
	E	US-5,930,331	07-1999	Rentzepis et al.	378/136
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

FORM PTO-1449 Sheet 1 of 1

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE	Atty Docket No. CIL-10626	Serial No.
INFORMATION DISCLOSURE STATEMENT STATEMENT BY APPLICANT (use several sheets if necessary)	Applicant Toshiki Tajima	Group 2881
	Filing Date	Examiner Nichita Wells

U.S. PATENT DOCUMENTS

Examiner Initial		Document Number	Date	Name	Class	Subclass	Filing Date If Appropriate
NW	1	RE034575	4/5/94	Klinkowstein, et al.	315	500	
	2	4,069,457	1/17/78	Martin, et al.	328	235	
	3	4,471,224	9/11/84	Cuomo, et al.	250	423	
	4	4,715,038	12/22/87	Fraser, et al.	372	2	
	5	4,937,532	6/26/90	Dawson, et al.	330	4.3	
	6	5,335,258	8/2/94	Whitlock	378	122	
	7	5,382,914	1/17/95	Hamm, et al.	315	505	
	8	5,394,411	2/28/95	Milchberg, et al.	372	5	
	9	5,412,283	5/2/95	Trone	315	5.41	
	10	5,440,133	8/8/95	Moyers, et al.	250	492.3	
	11	5,789,876	8/4/98	Umstadler, et al.	315	507	
NW	12	5,930,331	7/27/99	Rentzepis, et al.	378	136	

FOREIGN PATENT DOCUMENTS

		Document Number	Date	Country	Class	Subclass	Translation YES	Translation NO
NW	A	JP6068984 A	3/11/94	Japan				X
NW	B	JP7169597 A	7/4/95	Japan				X

OTHER DISCLOSURES (including Author, Title, Date, Pertinent Pages, Place of Publication, Etc.)

NW	1.1		T.E. Cowan, et al., "Photo-Nuclear Fission from High Energy Electrons from Ultra-Intense Laser-solid Interactions," UCRL-JC-137795, July 13, 1999, 15 pages
NW	1.2		T.E. Cowan, "High Energy Electrons, Nuclear Phenomena and Heating in Petawatt Laser-Solid Experiments," UCRL-JC-133031 Preprint, January 15, 1999, 13 pages
NW	1.3		B. Rau, et al.,"Strongly Nonlinear Magnetosonic Waves and Ion Acceleration," American Institute of Physics, Vol. 5, No. 10, October 1998, page(s) 3575-3580
NW	1.4		H. Hojo, et al., "Particle Acceleration and Coherent Radiation by Subcycle Laser Pulses," Nuclear Instruments & Methods in Physics Research, A 410, (1998) page(s) 509-513

Examiner Nichita Wells July 7, 2003

Examiner: initial if citation considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

FORM PTO-1449

Sheet 1 of 1

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE	Atty Docket No. CIL-10626	Serial No. 09/757,150
INFORMATION DISCLOSURE STATEMENT BY APPLICANT (use several sheets if necessary)	Applicant Toshiki Tajima	Group 2881
	Filing Date	Examiner N. Rita Wells

U.S. PATENT DOCUMENTS

Examiner Initial		Document Number	Date	Name	Class	Subclass	Filing Date If Appropriate

FOREIGN PATENT DOCUMENTS

		Document Number	Date	Country	Class	Subclass	Translation YES	Translation NO
AB	A	DE3616879	11/19/86	Germany				X

OTHER DISCLOSURES (including Author, Title, Date, Pertinent Pages, Place of Publication, Etc.)

Examiner Nikita Wells July 7, 2003

Examiner: initial if citation considered, whether or not citation is in conformance with MPEP 609. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

REVISED AMENDMENT PRACTICE: 37 CFR 1.121 CHANGED COMPLIANCE IS MANDATORY - Effective Date: July 30, 2003

All amendments filed on or after the effective date noted above must comply with revised 37 CFR 1.121. See Final Rule: **Changes To Implement Electronic Maintenance of Official Patent Application Records** (68 *Fed. Reg.* 38611 (June 30, 2003), posted on the Office's website at: http://www.uspto.gov/web/patents/ifw/ with related information. The amendment practice set forth in revised 37 CFR 1.121, and described below, replaces the voluntary revised amendment format available to applicants since February 2003. **NOTE: STRICT COMPLIANCE WITH THE REVISED 37 CFR 1.121 IS REQUIRED AS OF THE EFFECTIVE DATE (July 30, 2003).** The Office will notify applicants of amendments that are not accepted because they do not comply with revised 37 CFR 1.121 via a Notice of Non-Compliant Amendment. See MPEP 714.03 (Rev. 1, Feb. 2003). The non-compliant section(s) will have to be corrected and the entire corrected section(s) resubmitted within a set period.

Bold underlined italic font has been used below to highlight the major differences between the revised 37 CFR 1.121 and the voluntary revised amendment format that applicants could use since February, 2003.
Note: The amendment practice for **reissues** and **reexamination proceedings**, except for drawings, has not changed.

REVISED AMENDMENT PRACTICE

I. Begin each section of an amendment document on a separate sheet:
Each section of an amendment document (*e.g.*, Specification Amendments, Claim Amendments, Drawing Amendments, and Remarks) must begin on a separate sheet. Starting each separate section on a new page will facilitate the process of separately indexing and scanning each section of an amendment document for placement in an image file wrapper.

II. Two versions of amended part(s) no longer required:
37 CFR 1.121 has been revised to no longer require two versions (a clean version and a marked up version) of each replacement paragraph or section, or amended claim. Note, however, the requirements for a clean version and a marked up version for substitute specifications under 37 CFR 1.125 have been retained.

A) Amendments to the claims:
Each amendment document that includes a change to an existing claim, cancellation of a claim or submission of a new claim, **must include a complete listing** of all claims in the application. After each claim number in the listing, the status must be indicated in a parenthetical expression, and **the text of each pending claim** (with markings to show current changes) must be presented. The claims in the listing will replace all prior claims in the application.

(1) The current status of all of the claims in the application, including any previously canceled, not entered or withdrawn claims, must be given in a parenthetical expression following the claim number using only one of the following seven status identifiers: (original), (currently amended), (canceled), (withdrawn), (new), ***(previously presented) and (not entered).*** The text of all pending claims, ***including withdrawn claims,*** must be submitted each time any claim is amended. Canceled ***and not entered*** claims must be indicated by only the claim number and status, without presenting the text of the claims.

(2) The text of all claims being currently amended must be presented in the claim listing with markings to indicate the changes that have been made relative to the immediate prior version. The changes in any amended claim must be shown by underlining (for added matter) or strikethrough (for deleted matter) with 2 exceptions: (1) for ***deletion of five characters or fewer, double brackets may be used (e.g., [[eroor]]); and (2) if strikethrough cannot be easily perceived (e.g., deletion of the number "4" or certain punctuation marks), double brackets must be used (e.g., [[4]]). As an alternative to using double brackets, however, extra portions of text may be included before and after text being deleted, all in strikethrough, followed by including and underlining the extra text with the desired change*** (e.g., ~~number 4 as~~ ***number 14 as***). An accompanying clean version is not required and should not be presented. Only claims of the status "currently amended," and "withdrawn" that are being amended, may include markings.

(3) The text of pending claims not being currently amended, ***including withdrawn claims,*** must be presented in the claim listing in clean version, *i.e.*, without any markings. Any claim text presented in clean version will constitute an assertion that it has not been changed relative to the immediate prior version except to omit markings that may have been present in the immediate prior version of the claims.

(4) A claim being canceled must be listed in the claim listing with the status identifier "canceled"; the text of the claim must not be presented. Providing an instruction to cancel is optional.
(5) Any claims added by amendment must be presented in the claim listing with the status identifier "(new)"; the text of the claim must not be underlined.
(6) All of the claims in the claim listing must be presented in ascending numerical order. Consecutive canceled, or not entered, claims may be aggregated into one statement (*e.g.*, Claims 1 – 5 (canceled)).

Example of listing of claims (use of the word "claim" before the claim number is optional):

Claims 1-5 (canceled)

Claim 6 (previously presented): A bucket with a handle.

Claim 7 (withdrawn): A handle comprising an elongated wire.

Claim 8 (withdrawn): The handle of claim 7 further comprising a plastic grip.

Claim 9 (currently amended): A bucket with a ~~green~~ blue handle.

Claim 10 (original): The bucket of claim 9 wherein the handle is made of wood.

Claim 11 (canceled)

Claim 12 (not entered)

Claim 13 (new): A bucket with plastic sides and bottom.

B) Amendments to the specification:
Amendments to the specification, including the abstract, must be made by presenting a replacement paragraph or section or abstract marked up to show changes made relative to the immediate prior version. An accompanying clean version is not required and should not be presented. Newly added paragraphs or sections, including a new abstract (instead of a replacement abstract), must not be underlined. A replacement or new abstract must be submitted on a separate sheet, 37 CFR 1.72. If a substitute specification is being submitted to incorporate extensive amendments, both a clean version (which will be entered) and a marked up version must be submitted as per 37 CFR 1.125.

The changes in any replacement paragraph or section, or substitute specification must be shown by underlining (for added matter) or strikethrough (for deleted matter) with 2 exceptions: (1) for ***deletion of five characters or fewer, double brackets may be used (e.g., [[eroor]]); and (2) if strikethrough cannot be easily perceived (e.g., deletion of the number "4" or certain punctuation marks), double brackets must be used (e.g., [[4]]). As an alternative to using double brackets, however, extra portions of text may be included before and after text being deleted, all in strikethrough, followed by including and underlining the extra text with the desired change*** *(e.g., ~~number 4 as~~ number 14 as)*

C) Amendments to drawing figures:
Drawing changes must be made by presenting replacement figures which incorporate the desired changes and which comply with 37 CFR 1.84. An explanation of the changes made must be presented either in the drawing amendments, or remarks, section of the amendment, ***and may be accompanied by a marked-up copy of one or more of the figures being amended, with annotations.*** Any replacement drawing sheet must ***be identified in the top margin as "Replacement Sheet"*** and include all of the figures appearing on the immediate prior version of the sheet, even though only one figure may be amended. ***Any marked-up (annotated) copy showing changes must be labeled "Annotated Sheet Showing Changes" and accompany the replacement sheet as an appendix to the amendment.*** The figure or figure number of the amended drawing(s) must **not** be labeled as "amended." If the changes to the drawing figure(s) are not accepted by the examiner, applicant will be notified of any required corrective action in the next Office action. No further drawing submission will be required, unless applicant is notified.

Questions regarding the submission of amendments pursuant to the revised practice set forth in this flyer should be directed to: Elizabeth Dougherty or Gena Jones, Legal Advisors, or Joe Narcavage, Senior Special Projects Examiner, Office of Patent Legal Administration, by e-mail to patent.practice@uspto.gov or by phone at (703) 305-1616.

The United States Patent and Trademark Office has changed certain mailing addresses!

Effective May 1, 2003

Use the address **provided in this flyer after May 1, 2003** for **any correspondence** with the United States Patent and Trademark Office (USPTO) in patent-related matters to **organizations reporting to the Commissioner for Patents.**

DO NOT USE the Washington DC 20231 and P.O. Box 2327 Arlington, VA 22202 addresses after May 1, 2003 for **any correspondence** with the USPTO even if these old addresses are indicated in the accompanying Office action or Notice or in any other action, notice, material, form, instruction or *other* information.

Correspondence in patent-related matters to **organizations reporting to the Commissioner for Patents** must now be addressed to:

Commissioner for Patents
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Special Mail Stop designations to replace Special Box designations

Also effective May 1, 2003, the USPTO is changing the special Box designations for Patents and Trademarks to corresponding Mail Stop designations (*e.g.*, "Box 4" will now be "Mail Stop 4").

For further information, see *Correspondence with the United States Patent and Trademark Office*, 68 *Fed. Reg. 14332* (March 25, 2003). A copy of the *Federal Register* notice is available on the USPTO's web site at http://www.uspto.gov/web/menu/current.html#register

A listing of specific USPTO mailing addresses (See Patents – specific) will be available on the USPTO's web site on April 15, 2003 at http://www.uspto.gov/main/contacts.htm

Persons filing correspondence with the Office should check the rules of practice, the Official Gazette, or the Office's Internet Web site (www.uspto.gov) to determine the appropriate address and Mail Stop Designation (if applicable) for all correspondence being delivered to the USPTO via the United States Postal Service (USPS).

Questions regarding the content of this flyer should be directed to the Inventor Assistance Center at (703) 308-4357 or toll-free at 1-800-786-9199.

US005789876A

United States Patent [19]

Umstadter et al.

[11] Patent Number: 5,789,876

[45] Date of Patent: Aug. 4, 1998

[54] **METHOD AND APPARATUS FOR GENERATING AND ACCELERATING ULTRASHORT ELECTRON PULSES**

[75] Inventors: **Donald Umstadter**; **Joon-Koo Kim**; **Evan Dodd**, all of Ann Arbor, Mich.

[73] Assignee: **The Regents of the Univeristy of Michigan**, Ann Arbor, Mich.

[21] Appl. No.: **528,078**

[22] Filed: **Sep. 14, 1995**

[51] Int. Cl.[6] **H01J 23/00**

[52] U.S. Cl. **315/507**; 315/501; 315/505; 315/111.81

[58] Field of Search 315/507, 500, 315/505, 501, 111.81; 359/342; 378/119, 122

[56] **References Cited**

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(List continued on next page.)

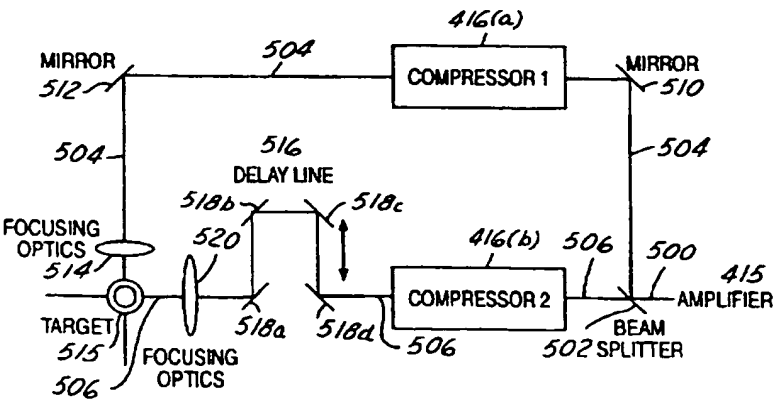
Primary Examiner—Ashok Patel

Attorney, Agent, or Firm—Barnes, Kisselle, Raisch, Choate, Whittemore & Hulbert, P.C.

[57] **ABSTRACT**

The invention provides a novel laser-plasma-based source of relativistic electrons; and a method to use laser-driven plasma waves as the basis for the source of electrons. The technique involves a combination of laser beams, which are focused in a plasma. One beam creates a wakefield plasma wave. In one embodiment, the one beam creates a wakefield plasma wave and the other beam alters the trajectory of background electrons, such that they become trapped in the plasma wave and are then accelerated to relativistic velocities, preferably in a distance less than a millimeter. In another embodiment, the second beam removes electrons from atomic ions previously generated by the first beam thereby providing electrons which become trapped in the plasma wave and then accelerated to relativistic velocities.

48 Claims, 8 Drawing Sheets



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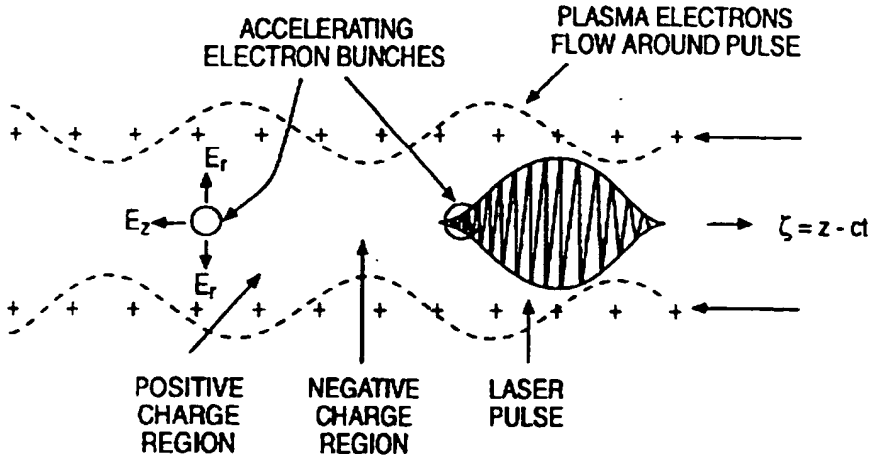


FIG. 1

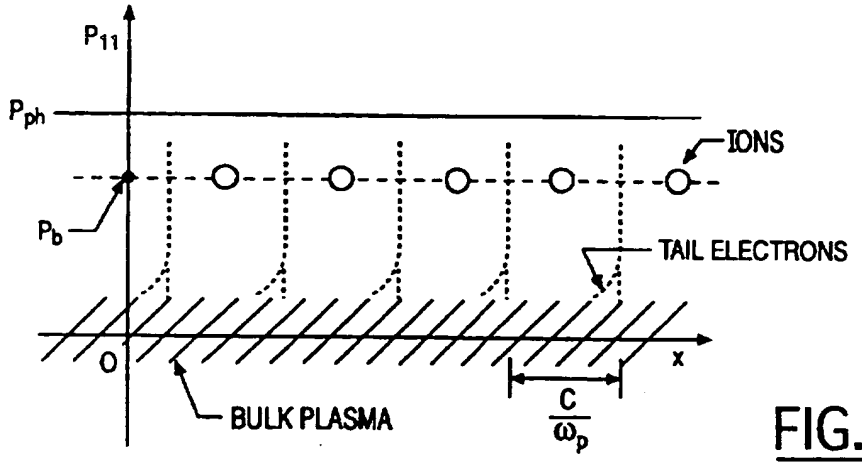


FIG. 2

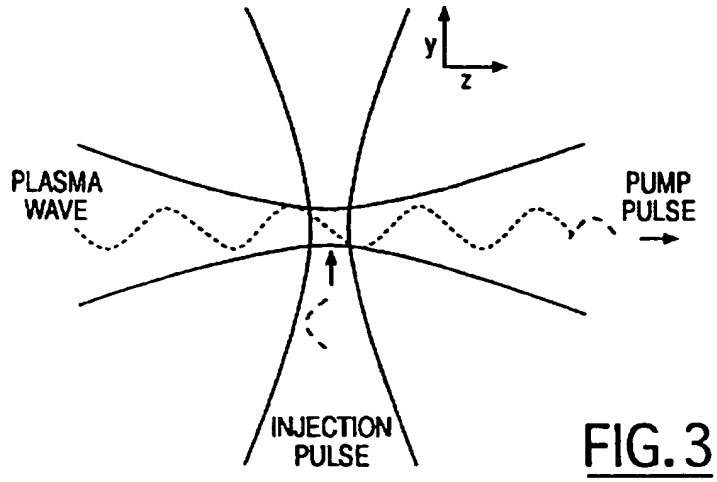


FIG. 3

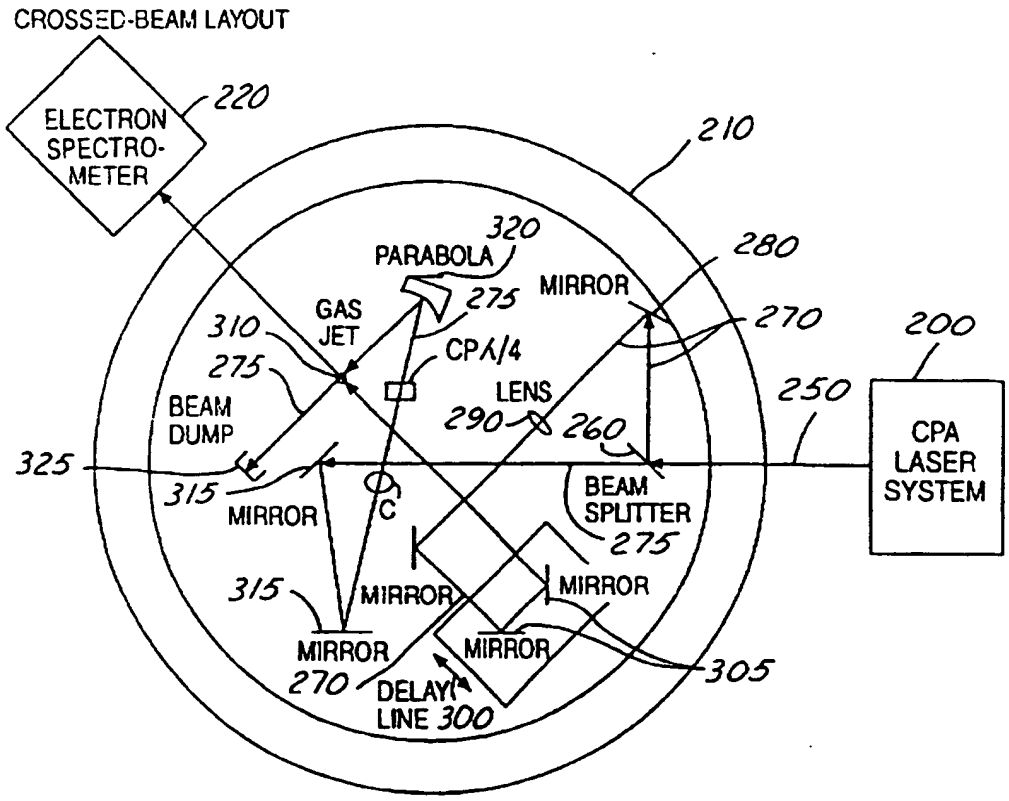

CROSSED-BEAM LAYOUT
ELECTRON SPECTRO-METER
220
210
320
PARABOLA
280
MIRROR
275
GAS JET
310
270
200
CPλ/4
275
LENS
250
BEAM DUMP
290
260
CPA LASER SYSTEM
325
315
MIRROR
C
BEAM SPLITTER
275
315
MIRROR
MIRROR
MIRROR
MIRROR
270
305
DELAY LINE 300

FIG. 4

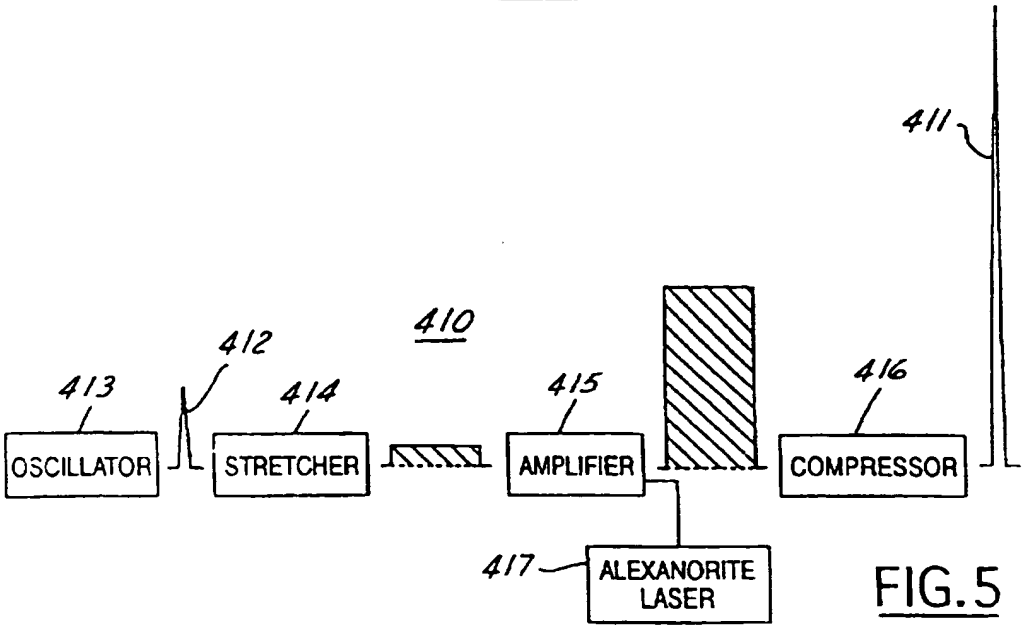
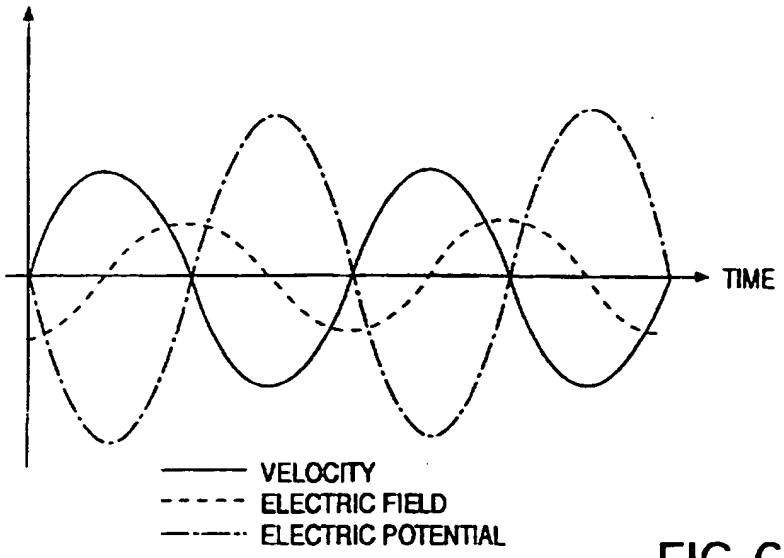
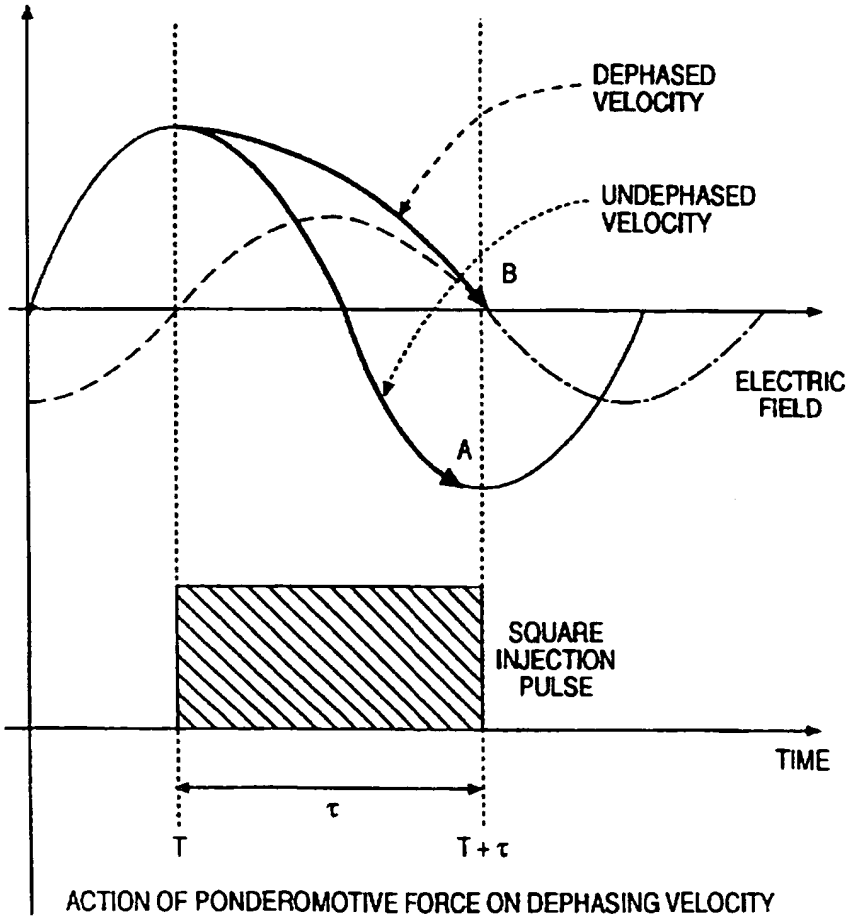

411
410
412
413
414
415
416
OSCILLATOR
STRETCHER
AMPLIFIER
COMPRESSOR
417
ALEXANORITE LASER

FIG. 5



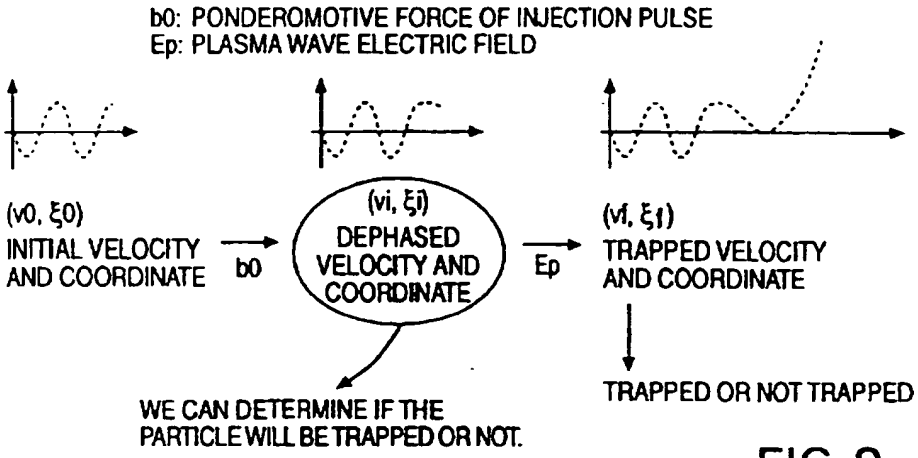
PHASE RELATIONSHIPS

FIG. 6



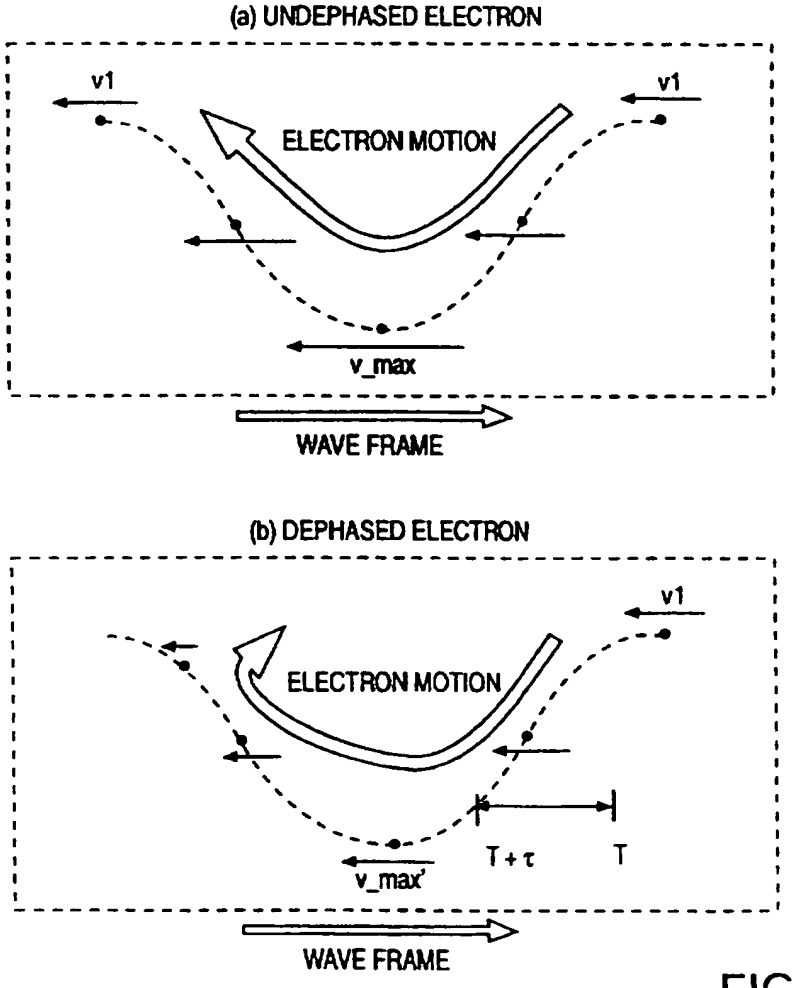
ACTION OF PONDEROMOTIVE FORCE ON DEPHASING VELOCITY

FIG. 7



3-STAGE OPERATION OF LILAC

FIG.8



MOTION OF NORMAL AND LILAC ELECTRON

FIG.9

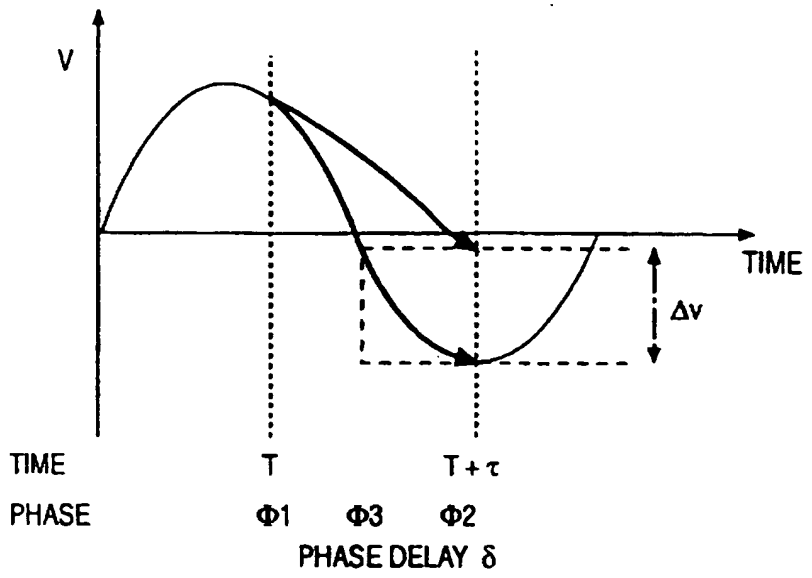
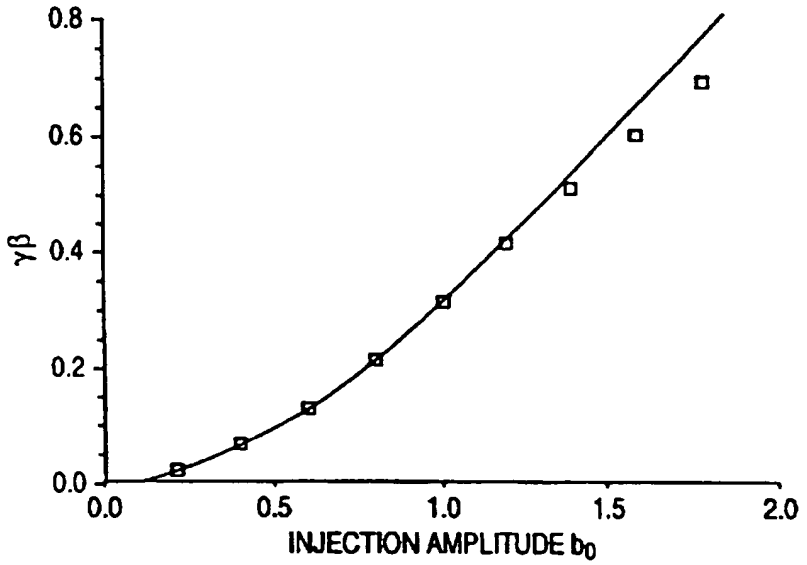
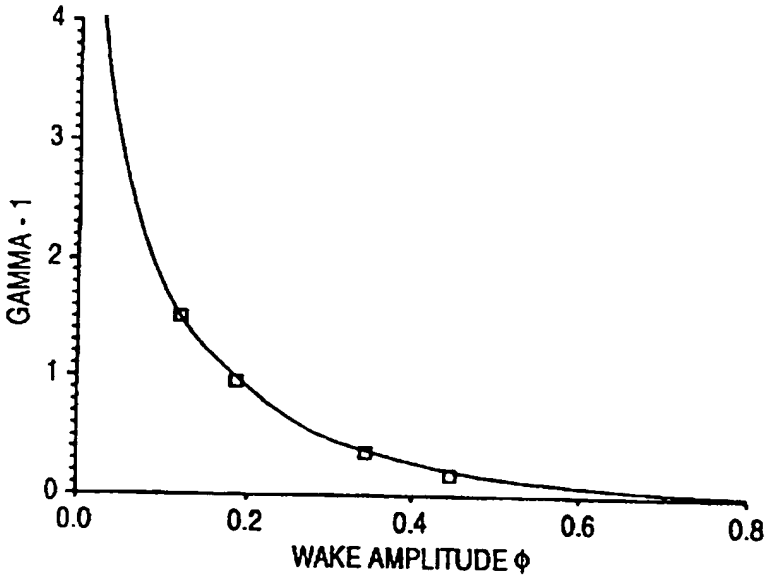


FIG. 10



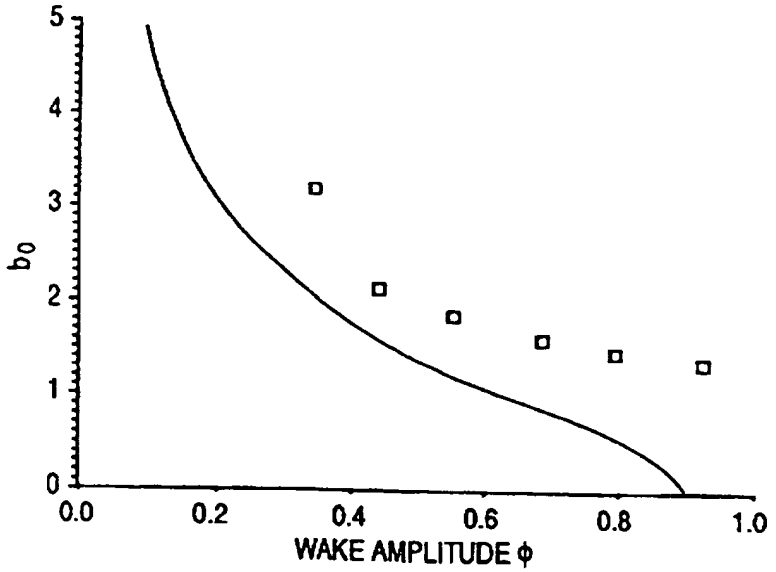
FINAL DRIFT VELOCITY VS. LASER PULSE AMPLITUDE

FIG. 11



WAKE AMPLITUDE VS. INJECTION THRESHOLD T - 1

FIG. 12



WAKE AMPLITUDE VS. LILAC INJECTION THRESHOLD b_0

FIG. 13

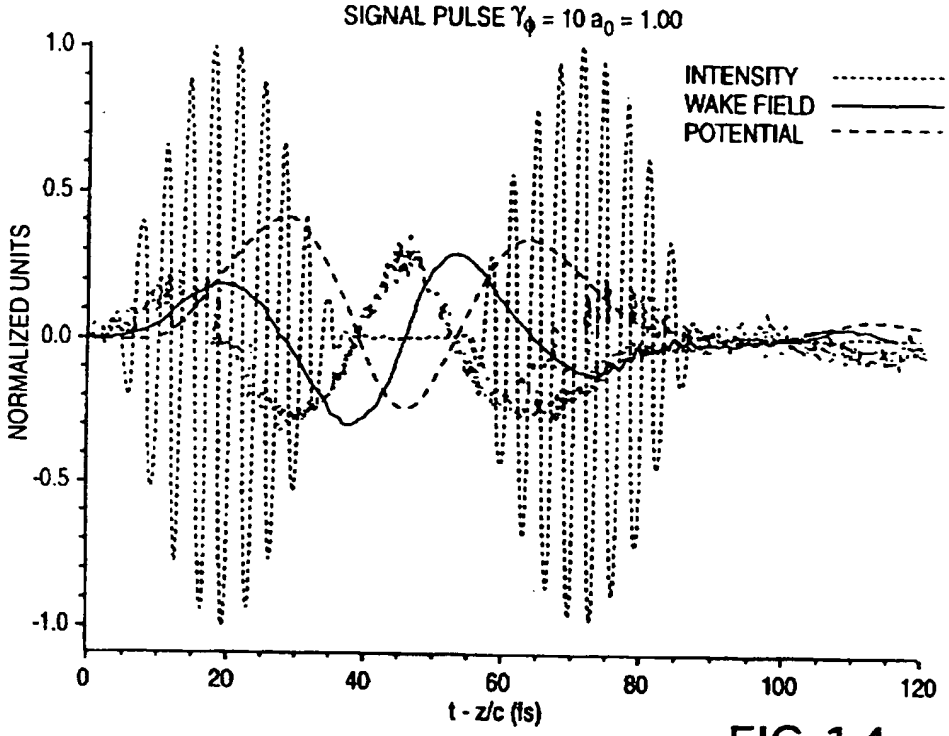

SIGNAL PULSE γ_ϕ = 10 a_0 = 1.00
INTENSITY
WAKE FIELD
POTENTIAL
NORMALIZED UNITS
1.0
0.5
0.0
-0.5
-1.0
0
20
40
60
80
100
120
t - z/c (fs)

FIG. 14

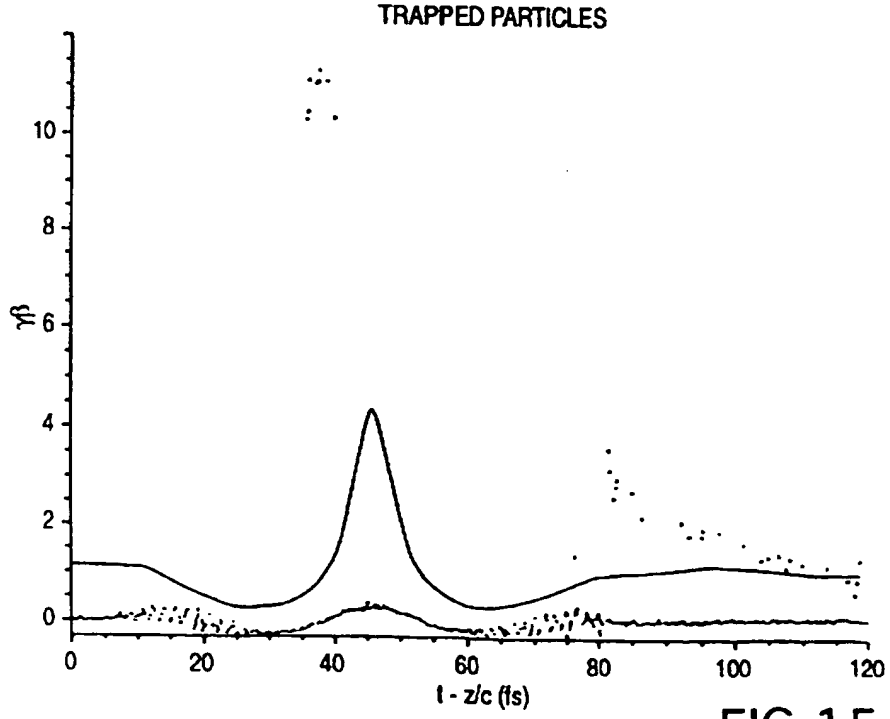

TRAPPED PARTICLES
γβ
10
8
6
4
2
0
0
20
40
60
80
100
120
t - z/c (fs)

FIG. 15

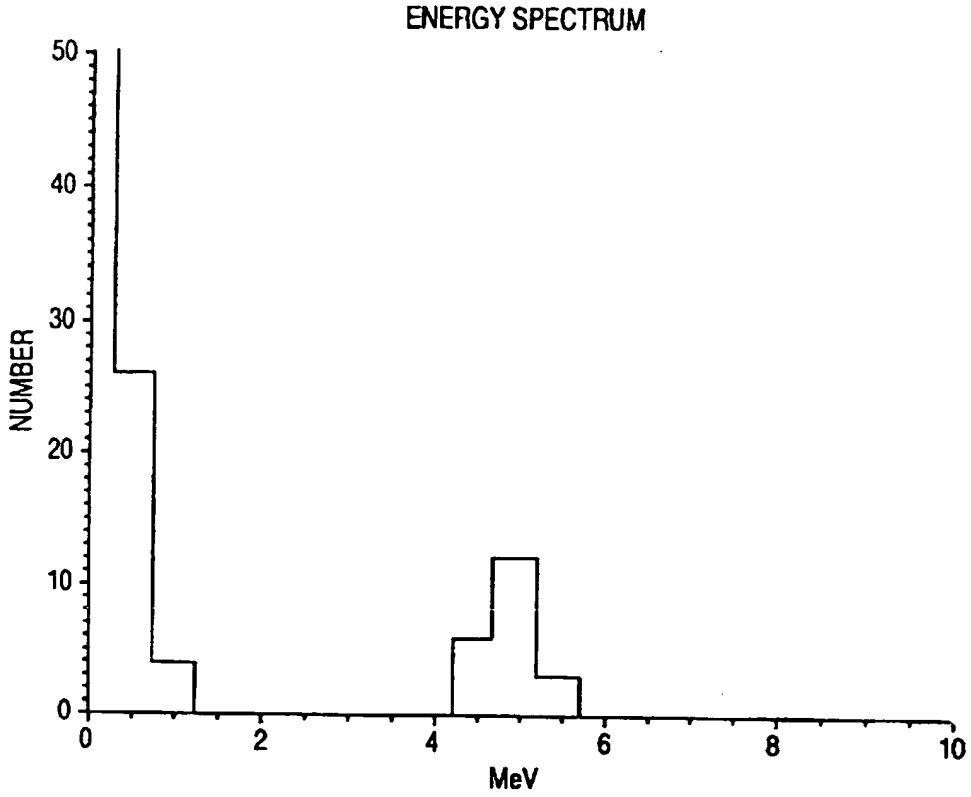

ENERGY SPECTRUM
NUMBER
50
40
30
20
10
0
0
2
4
6
8
10
MeV

FIG. 16

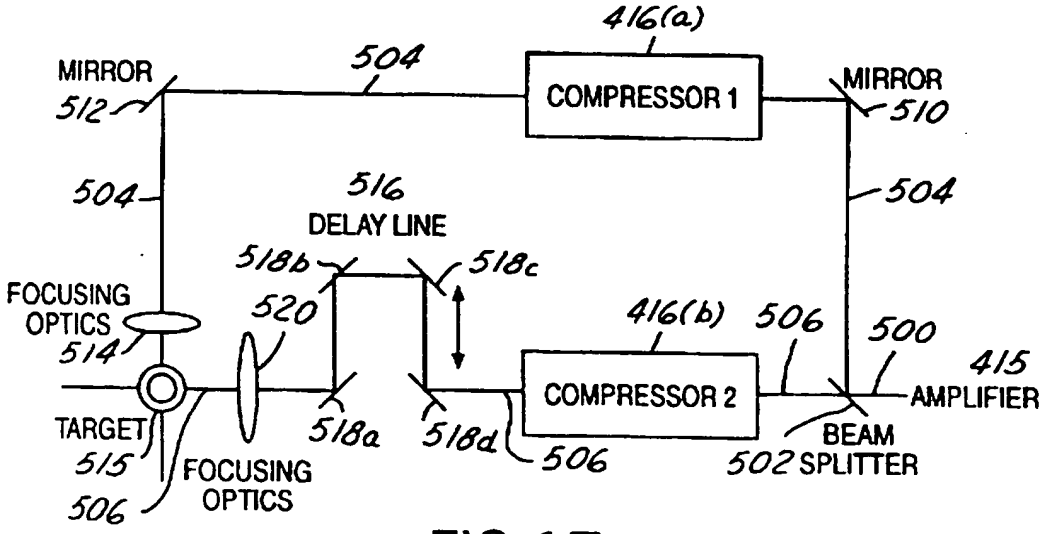

416(a)
MIRROR
512
504
COMPRESSOR 1
MIRROR
510
504
504
516
DELAY LINE
518b
518c
FOCUSING
OPTICS
514
520
416(b)
506
500
415
AMPLIFIER
COMPRESSOR 2
TARGET
515
506
FOCUSING
OPTICS
518a
518d
506
BEAM
502 SPLITTER

FIG. 17

METHOD AND APPARATUS FOR GENERATING AND ACCELERATING ULTRASHORT ELECTRON PULSES

GOVERNEMENT'S RIGHT CLAUSE

This invention was made with government support provided by the National Science Foundation. The government has certain rights in the invention.

FIELD OF THE INVENTION

This invention relates to a method and apparatus for accelerating particles in a plasma and more particularly to a method and apparatus of accelerating electrons to relativistic velocities.

BACKGROUND OF THE INVENTION

Since 1927, when Rutherford first proposed they be built, linear accelerators (linacs) have used either dc high-voltage or radio-frequency electric fields in vacuum to directly accelerate electrons from rest to MeV energies.

Current techniques for generating large amplitude plasma waves differ from each other essentially only in the temporal characteristics of the driving laser pulse(s), relative to the temporal characteristics of the plasma wave. For instance, the laser wakefield accelerator (LWFA) (FIG. 1) uses a single pulse with a pulsewidth $\tau \sim 2\pi/\omega_p$ where ω_p is the plasma frequency. The plasma beatwave accelerator (PBWA) (FIG. 2) uses a series of pulses of equal pulsewidths and equally spaced $\tau \sim 2\pi/\omega_p$. The self-modulated LWFA (SM-LWFA) and stimulated Raman forward scattering (SRFS), which are closely related, both use a single pulsewidth $\tau >> 2\pi/\omega_p$.

A plasma wave is an attractive acceleration medium because electrons can be accelerated to an energy of 3 GeV over a distance on the order of several meters. Besides applications in high-energy physics, the accelerated electrons can also be used to produce tunable short-wavelength radiation, either Bremstrahlung radiation from striking an anode as in an x-ray tube, or synchrotron radiation when they are passed through undulator magnets as in conventional synchrotron light sources of free-electron lasers, or when they collide (Compton scatter) with a laser pulse. Either the electrons themselves, or the high-energy photons into which they can be converted, have numerous industrial, medical and scientific applications, including: lithography, microscopy, spectroscopy, diffraction, metallurgy, radiology, oncology, and sterilization.

Conventional linacs produce an energy spread of accelerated electrons that is too great to be useful for most applications which require small electron-beam-energy spread. Conventional linacs are not able to produce a high-flux, small emittance, ultrashort-duration electron beam.

Accordingly, what is needed is a new method and apparatus to produce a high-flux, small-emittance, ultrashort electron beam.

SUMMARY OF THE INVENTION

The invention provides a novel laser-plasma-based source of relativistic electrons; and a method to use laser-driven plasma waves as the basis for the source of electrons. The technique involves a combination of laser beams, which are focused in a plasma. One beam creates a wakefield plasma wave.

In one embodiment, the one beam creates a wakefield plasma wave and the other beam alters the trajectory of background electrons, such that they become trapped in the plasma wave and are then accelerated to relativistic velocities, preferably in a distance less than a millimeter. In another embodiment, the second beam removes electrons from atomic ions previously generated by the first beam thereby providing electrons which become trapped in the plasma wave and then accelerated to relativistic velocities in the aforesaid short distance. For simplicity, the first beam is referred to as the pump pulse and the second beam is referred to as the injection pulse. In one aspect of the invention, acceleration of electrons is made possible by dephasing the electrons with respect to the plasma wave by using ponderomotive force. In another aspect, the dephased electrons are also created essentially instantaneously at a given point in the plasma wave by the injection pulse which removes electrons from atomic species in the plasma at a higher ionization stage than that of the electrons previously removed by ionization by the pump pulse which forms the plasma wave. Combinations of various numbers of pulses at varying intensities, pulse time duration (pulsewidth), wavelength, and polarization are used to achieve the dephased electrons for acceleration.

In one embodiment, a single pump pulse and a single injection pulse are used where the pump and injection beams are orthogonal to one another. In another embodiment, two injection pulses are used which are delivered in a beam in a direction orthogonal to the pump pulse beam. The two injection beams are counter-propagating, that is, opposite to one another. In still another embodiment, the pump pulse is followed by an injection pulse which is collinear with the pump pulse but is at a higher intensity.

In still another embodiment, first and second pump pulses are used along with an injection pulse. The second pump pulse is generated at an interval of 3/2 plasma wavelengths $(3/2\lambda_p)$ after the first pump pulse, to provide an acceleration region of a single plasma wavelength and thus provide a single accelerated electron bunch.

In still another embodiment, the pump pulse causes the plasma wave which has an axial dimension (z axis) and a radial dimension (y axis); and the injection pulse is focused onto the plasma wave by focusing means which provides a beam spot size having a dimension along the y axis which is greater than the size along the z axis. Preferably, the injection pulse is focused onto the plasma wave by focusing means which provides a beam spot size, which in one dimension substantially corresponds to the radial extent of the plasma wave, and in another dimension corresponds to about one plasma wave wavelength (λ_p). The method of the invention locally disturbs the plasma wave and generates a group of electrons that are dephased with respect to the plasma wave and thereby come under the influence of the electric field of the plasma wave permitting such electrons to be accelerated. As a result, the invention provides both the source of accelerated electrons as well as the means for their acceleration. This avoids cumbersome conventional apparatus and methods which require separate expensive systems for generating electrons, i.e., electron guns, and for accelerating electrons, i.e., linear acceleration (linac).

In still another embodiment, two pump pulses are used. A first pump pulse generates the plasma and the second pump pulse creates the plasma wave. The first pump pulse ionizes the plasma to high ionization stage and the second pump pulse, delayed by greater than several ion periods creates a plasma wave after the plasma wave from the first pump pulse has damped away, but not after plasma recombination. A third pulse which is the injection pulse ionizes the plasma one stage further and injects electrons with high velocity.

The maximum residual velocity of the electrons depends on the intensity at which such electrons were created by ionization. In this embodiment, desirably the pump pulse and the injection pulse have differing polarizations. In this embodiment, the injection pulse is preferably circularly polarized and the other pulses, pump pulses, are linearly polarized. Other combinations besides linear and circular polarization are also possible, namely, elliptical polarization variations. This approach decouples the plasma wave generation from the ionization, thus avoiding a change in plasma density during the second pump pulse.

In the method of the invention, if it is desired to accelerate electrons by changing trajectory via ponderomotive force only, it is preferable to use hydrogen, which has one electron. If it is desired to generate a group of dephased electrons by removing electrons from atomic ions in the plasma, then it is preferable to use a higher order atom, such as, for example, argon.

It should be noted that the disturbance necessary to generate the dephased electrons does not totally destroy the plasma wave. The disturbance is localized in the direction of the pump pulse. In the case of a transverse injection beam, it propagates in a direction which does not disturb the rest of the plasma wave momentarily since the disturbance by ponderomotive force propagates in the direction of the pump pulse at a much slower speed compared to the phase velocity of the plasma wave. If a wake is created by the transverse injection beam moving along a y axis perpendicular to a z axis, it does not propagate in the direction of the pump pulse (along z axis) at nearly the same velocity as either the wake of the pump pulse or the trapped electrons. Therefore, when the injection pulse arrives it pushes electrons radially (in the z direction in the plane of the y axis) so as to dephase their normal orbits. This disturbance does propagate in the z direction which is the direction of the pump pulse. However, the velocity at which the wave is moving is much higher than the velocity at which the disturbance moves. As a result, it is possible to dephase a group of electrons, accelerate them, and achieve a final accelerated bunch of electrons which are essentially mono-energetic, where all of the electrons have essentially the same energy, or very close to the same energy, for example, plus or minus 10 percent. The pulse width of the accelerated electrons is ultrashort and approaches the pulsewidth of the laser that generated them and may even be shorter.

Importantly, the pulses of the invention are ultrashort pulses generated by a specific configuration of a laser system as described herein. In the method of the invention, the pump pulse and the injection pulse may be obtained from the same laser beam by splitting a single laser pulse into two sub-pulses, one of which is used as the injection pulse and the other of which is used as the pump pulse. The beam-splitting may occur before or after recompression in the laser system. If such beamsplitting occurs after recompression, then the pump and injection pulses are synchronized with respect to one another. Such synchronization is very difficult to achieve by conventional systems which require independent devices, one being an electron generator and the other being the laser to produce a plasma wave. The invention may also be used with the beamsplitter prior to recompression, in order to achieve pump pulse and injection pulse of different pulse time durations.

The invention advantageously utilizes laser-driven plasma waves as the first-stage low-energy electron gun/linac itself. As such, it forms the basis for a compact (table-top) source of relativistic electrons, that can either be used by itself or as an injector for high-energy accelerators. Electrons are accelerated to relativistic velocities in a distance less than a millimeter, as compared with several meters for a comparable conventional linac. This results in lower beam emittance and a more compact size. It also produces much shorter-duration electron pulses (femtosecond as compared with picosecond). For applications that require an electron bunch synchronized with a laser-light pulse, femtosecond accuracy may be achieved with the invention. Two orthogonally directed laser beams are injected into a plasma: one beam creates a wakefield plasma wave, and the other alters the trajectory of background electrons in such a way that they become trapped in the plasma wave and are then accelerated to relativistic velocities in a distance less than a millimeter. As the technique involves the injection of electrons by a laser beam, it is referred to as the Laser-Injected Laser ACcelerator (LILAC). Compared with a conventional electron linac, the LILAC has a much higher field gradient, resulting in lower beam emittance. Since it also can produce much shorter-duration electron pulses, it can be used for the study of ultrafast dynamics on femtosecond timescales. The invention also enables femtosecond-synchronization between the electron bunch and the plasma wave acceleration field, which is required to achieve a low-energy spread for the accelerated electrons. A high-flux low-emittance beam of 20-MeV electrons can be produced with a currently-available table-top high-intensity laser ($I \leq 1 \times 10^{18}$ W/cm^2). The principle upon which the LILAC is based can be used to study the growth of, and the trapping of electrons in, laser wakefield plasma waves.

Advantageously, the invention (LILAC) provides an improved method and apparatus to accelerate electrons. It is capable of accelerating electrons from rest to energies ranging anywhere from an MeV to greater than a GeV (with optical guiding). The invention (LILAC) can produce a high-flux, small-emittance, ultrashort-duration (subpicosecond) electron beam. For applications requiring a single ultrashort bunch of electrons, such as ultrafast dynamical studies, a single bucket can be generated. This novel electron gun could serve several purposes: (1) as a stand-alone accelerator system, (2) as a low emittance injection stage for conventional accelerators, or (3) as a means to study the physics of laser-wakefield plasma waves. Accordingly, femtosecond synchronization between the electron bunch and a single-plasma-wave-acceleration bucket is made possible for the first time by the invention.

Advantageously, the invention provides, high flux, small emittance (beam energy spread) and ultrashort duration (subpicosecond) electron beam.

Accordingly it is a general object of the invention to provide a method and apparatus for producing electrons accelerated to relativistic velocities.

Another object is to provide a method and apparatus for creating dephased electrons, dephased with respect to a plasma wave for acceleration of said electrons via plasma wave electric field.

Another object is to provide a combination of laser pulses having a combination of characteristics and direction with respect to one another where one beam creates a wakefield plasma wave and the other beam alters the trajectory of background electrons for trapping by the plasma wave and acceleration to relativistic velocities.

Still another object is to provide a combination of laser beams which form a plasma, form a plasma wave in the plasma, and inject electrons for acceleration to relativistic velocities, without the need for a separate conventional electron source.

Still another object is to provide femtosecond duration electron pulses produced by a combination of laser beams.

Still another object is to provide electrons accelerated to relativistic velocities in a distance less than a meter, and in as little as a millimeter or less.

These and other objects, features, and advantages of the invention will become apparent from the following description of the preferred embodiments, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic of a laser wakefield accelerator (LWFA) showing the ponderomotive force from a laser pulse generating a plasma wave wake in a plasma.

FIG. 2 is a schematic phase space diagram showing bulk electrons, tail electrons, and pre-accelerated ions where P_{ph} represents the phase momentum of the plasma wave excited by laser and P_b is the ion beam momentum, ion clump separation is designated as c/ω_p.

FIG. 3 shows a schematic of the laser injected laser accelerator concept of the invention.

FIGS. 4 and 17 are schematic diagrams of the laser injected laser accelerator (LILAC) experimental systems of the invention.

FIG. 5 is a schematic representation of a chirped pulse amplification (CPA) arrangement.

FIG. 6 is a schematic showing the phase relationships among electron velocity, plasma wave electric field, and plasma wave field electric potential.

FIG. 7 is a schematic showing the action of ponderomotive force of the injection beam causing the dephasing electron velocity, curve B, compared to undephased velocity, curve A.

FIG. 8 is a schematic representation of the three stage operation of the LILAC of the invention.

FIGS. 9*a* and 9*b*, are schematic representations showing motion of an undephased electron (9*a*); and motion of a dephased electron (9*b*) in the plasma wave frame of reference.

FIG. 10 is a schematic showing phase delay δ.

FIG. 11 is a plot showing electron final drift velocity along the direction perpendicular to the propagation of the injection pulse as a function of the injection amplitude.

FIG. 12 is a plot of the trapping formula shown as Equation 4.33 in Table I where trapping is simulated for waves of various amplitude.

FIG. 13 is a plot where the solid line represents the curve that is obtained from coupling the trapping and drift velocity formulas directly; the dotted line is the numerical solution of the model; and the rectangular points are obtained from the simulation of wakefield amplitude versus injection threshold.

FIG. 14 is a plot of the simulation showing the wave propagating through the plasma in the frame of the moving wave. The four points plotted are: laser intensity is given as small dots; electric field of the wake is given as a solid line; electric potential is given as a dashed line; and individual particle velocities are given as large black dots. The first three quantities are noted on the legend of the plot. The velocities are plotted as individual points on the plot.

FIG. 15 is a plot of time normalized momenta of the particles, $\gamma\beta$. The solid line represents the trapping condition of Equation 4.33, any particle with a momentum above this line is trapped. At 37 fs (femtoseconds) particles can be seen well above the trapping condition.

FIG. 16 is a plot showing the energy spectrum of the electrons at the end of the simulation. There are two groups represented. The first is the background electrons with energies of 0 to 1 MeV and the second group is centered at 5 MeV and are the electrons in the beam.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Before describing the invention in detail, it is useful to understand the problems associated with present acceleration methods.

Current laser-driven plasma waves have been used, or proposed to be used, exclusively for second-stage high-energy electron acceleration of a trailing bunch of electrons. In this case, prior to injection into the plasma wave, the trailing bunch of electrons must first be generated and pre-accelerated ($\gamma mc^2 \leqq 5$ MeV) by means of a conventional electron gun/accelerator, such as a medical linac (radio-frequency) or Van de Graaff generator (dc).

Current techniques for generating large amplitude plasma waves differ from each other essentially only in the temporal characteristics of the driving laser pulse(s), relative to the temporal characteristics of the plasma wave. For instance, the laser wakefield accelerator (LWFA) (FIG. 1) uses a single pulse with a pulsewidth $\tau \sim \pi/\omega_p$, where ω_p is the plasma frequency. The plasma beatwave accelerator (PBWA) (FIG. 2) uses a series of pulses of equal pulsewidths and equally spaced $\tau \sim \pi/\omega_p$. The self-modulated LWFA (SM-LWFA) and stimulated Raman forward scattering (SRFS), which are closely related, both use a single pulse with $\tau >> 2\pi/\omega_p$.

All of these current techniques for accelerating electrons with a plasma wave involve the acceleration of a trailing bunch of properly-phased electrons. The injection threshold (the energy at which the electrons become trapped by the wave) depends on both the plasma-wave amplitude and phase velocity, obtained by setting the plasma wave potential equal to the electron's kinetic energy (in the wave frame). In order to be trapped by, and thus gain energy from, a plasma wave, the electrons must already have significant kinetic energy. The lower the plasma wave amplitude, and the higher the value of γ_p, the higher the kinetic energy required, where $\gamma_p = (1 - v_p^2/c^2)^{-1/2}$, and v_p is the plasma-wave phase velocity. Background plasma wave electrons, which oscillate in-phase with each other, will not be accelerated until the plasma wave reaches the wavebreaking amplitude, $E_{WB} = E_0\sqrt{2(\gamma_p - 1)}$, where $E_0 = (m_e c\omega_p/e) \equiv 0.96 n_e^{1/2}[\text{cm}^{-3}]\text{V/cm}$. Even if the plasma wave breaks, the energy spread of any electrons that are accelerated in this way will be too large to be useful for most applications, which require small electron-beam-energy spread.

For this reason, conventional low-energy electron linacs (such as those that use microwave cavities) are used to first accelerate a trailing bunch of electrons from rest up to the required injection energies. Typically, these have low-field gradients (6.5 MeV/m), and, for a short-pulse synchronized electron bunch, have a laser-triggered photocathode for the electron source. Coupling the electron bunch generated by this linac to a laser-plasma accelerator is quite difficult and complicated, requiring precise temporal and spatial overlap with micron accuracy. Even with state-of-the-art electrons guns, the pulsewidth of the electron bunch is considerably longer ($\tau \geqq 5$ ps) than a plasma wave period ($\tau \leqq 1$ ps). For this reason, multiple acceleration buckets are filled uniformly in-phase space, resulting in a large-energy spread of the accelerated electrons and several bunches. More than a

single bunch per pulse would make ultrafast studies difficult. Also, in a conventional electron gun/high-energy accelerator system, the largest electron-emittance growth occurs due to dispersion over the long-acceleration lengths of the low-energy first-stage conventional electron linac.

The invention provides a new method and apparatus for obtaining relativistic electrons. This system is unlike other plasma-based accelerators, which are exclusively second stage electronic accelerators requiring a trailing bunch of electrons that have been generated and pre-accelerated in a conventional combination electron gun and linear accelerator. The invention provides a method and apparatus to use laser driven plasma wave in place of the less effective conventional electron gun/linear accelerator. The method involves a combination of laser pulses focused in a plasma in a particular manner, as shown in FIG. 3.

In the description of the invention, the following terms are used: (1) ion period is the time it takes for ions to have a single cycle in plasma oscillation; (2) recombination is the reverse process of ionization of neutral atoms; (3) damped away refers to the plasma wave amplitude, either can increase or decrease by the wave particle interaction called Landau damping; (4) residual velocity refers to the situation when laser intensity reaches Above Threshold Ionization (ATI) intensity, plasma electrons are born from neutral atoms with certain velocity, this is called residual velocity; (5) trapped refers to the situation if the kinetic energy of a particle is less than the potential energy of the wave in the reference frame of the wave, then the particle is said to be trapped in the wave; and (6) drift velocity is analogous to residual velocity and refers to velocity imparted by ponderomotive force.

The invention provides a novel laser-plasma-based source of relativistic electrons; and a method to use laser-driven plasma waves as the basis for the source of electrons. The technique involves a combination of laser beams, which are focused in a plasma. One beam creates a wakefield plasma wave. In one embodiment, another beam (injection pulse) alters the trajectory of background electrons, such that they become trapped in the plasma wave and are then accelerated to relativistic velocities in a distance preferably less than a millimeter.

The wakefield plasma wave of the invention is driven by a pump beam. In one embodiment, a pump beam of a single pulse is used as the laser wakefield accelerator. The pump beam and the wakefield plasma wave are co-propagating. The other beam (the injection beam) is used to trap electrons in the plasma wave wakefield. A variably-delayed injection pulse, propagating in the direction perpendicular to the propagation direction of a wakefield plasma wave, is brought to a focus on the plasma wave, preferably at an optimum point in space and time. It changes the trajectories of background electrons (oscillating in the plasma wave) such that they become trapped and accelerated by the plasma wave. In this embodiment, it is the ponderomotive force due to the transverse field gradient of the injection pulse that gives rise to the change in-phase and trapping of background electrons.

The injection pulse also has a longitudinal ponderomotive force, which can have deleterious effects: it can either (1) accelerate electrons in a direction orthogonal to that of the pump's wakefield or (2) create its own wake. In order to mitigate these effects, two counterpropagating injection beams are used to create longitudinal ponderomotive forces that cancel each other at the intersection point (a standing wave). This alternative may be preferred for some applications, but is not thought strictly necessary. The reasons are as follows. In the case of (1), even if electrons are given an initial kick in the direction orthogonal to the pump's wake, it will be quite small compared with the acceleration they feel once trapped by the wakefield. Since they all get the same kick, once they are accelerated to their final energy, they will all leave with the same small angle relative to the direction of the pump beam. So long as the electrons do not move in the transverse direction a distance more than a plasma wave radius, this initial kick should not be a problem, since it is only angular spread that increases electron-beam emittance. In the case of (2), even if a disturbance is created in the direction of the pump pulse by the transverse beam, it does not propagate in the direction of the pump at nearly the same velocity as either the wake of the pump or the trapped electrons. Thus, shortly after being injected, the trapped electrons will find themselves in an undisturbed region of the wave created by the pump. If necessary, the disturbance can be eliminated altogether if the transverse beam's pulse duration is adjusted so that it is wakeless, i.e., out of resonance with the plasma.

In another embodiment, the invention provides independent adjustment of the pulse duration of the injection pulse. Under certain circumstances, this could result in the injection of pulses into several buckets, for example, if it is longer than a plasma wave period, or the width of the plasma wave is greater than a plasma wavelength. Thus, if acceleration of just a single bunch of electrons is desired, only a single acceleration bucket must be created. This is accomplished by use of two pump pulses. The first pulse can be used to drive up the plasma wave, and the second, by arriving one and a half plasma periods later, can be used to drive it back down. Conversely, if it is desirable to fill several buckets, then this may be accomplished by use of either a long injection pulse or a train of injection pulses.

The method of accelerating electrons that are out of phase with a plasma wave is quite general. There are alternative embodiments, besides the use of the ponderomotive force of an injection pulse. For instance the injection pulse is used to create the out-of-phase (dephased) electrons by multiphoton, or tunneling, photo-ionization. In this case, a gas comprising an atom with several electrons is used. The pump pulse at its peak intensity ionizes the gas to a given ionization stage, then the injection pulse ionizes the gas further to a higher ionization stage, creating electrons that are out of phase with the plasma wave. These electrons are then accelerated in a manner similar to that discussed above.

If the ionization occurs at sufficiently high intensity, the electrons can be born (created) with a high enough residual velocity to become trapped in the plasma wakefield. In the case of circularly polarized light, the residual (drift) velocity is equal to the quiver velocity and is in a direction perpendicular to the direction of the laser electric field at the time when it was born. In the case of linearly polarized light, the residual energy is significantly less, equal to a fraction of the ponderomotive potential energy, and the drift velocity is along the direction of the laser electric field. Since the electric field vector rotates in the case of circularly polarized light, only a small fraction of the electrons created by ionization would be in the right direction to be injected, and the angular spread of the injected electrons would be higher, in comparison with the case of linear polarization.

A given ionization stage has a threshold that is proportional to both the laser intensity and the laser wavelength—the shorter the wavelength, the lower the intensity required for ionization. Accordingly, if the injection pulse is shorter wavelength than the pump, it can reach the required higher

ionization stage with an intensity that is the same as, or even lower than, that of the pump. The use of circularly polarized light for the injection pulse increases the residual velocity of the ionized electrons for a given laser intensity, as compared with a linearly polarized pulse. Thus, the use of either short wavelength or circularly polarized light reduces the deleterious effect of the ponderomotive force of the injection pulse on the plasma wakefield.

In one embodiment, the injection pulse is orthogonal to the pump pulse. In another embodiment, the injection pulse is collinear with the pump pulse, considerably simplifying the alignment of the two pulses. In this regard, the laser pulses are generated by a resonant laser-plasma accelerator (RLPA). The RLPA uses a series of pulses with increasing spacing between them and decreasing pulsewidths to compensate for the change in resonance as the plasma wave grows and ω_p changes. In the collinear case, not only does the second pulse create dephased electrons, it is used to enhance the wake of the pump pulse. Circularly polarized pulses are preferably used in order to create the electrons with a high initial forward velocity and thus increase the number of trapped electrons. In the collinear case, the second pump pulse achieves two objectives. It creates dephased electrons and also enhances the wake of the first pump pulse. Circularly polarized pulses are preferably used in order to create the electrons with a high enough initial forward velocity to be trapped. However, in order to produce high axial electric fields, short focal lengths are required, which, without some method for channeling the beams, would reduce the acceleration length.

The basic system used for the laser-plasma interaction, preferably includes a plasma region that is located at the center of a vacuum chamber. A vacuum is necessary in order to avoid degradation of the high-intensity laser beam due to self-phase modulation. The electrons are coupled out of the vacuum through a thin-film-metal window. The plasma is created either by laser photo-ionization of a gas or by other means. The pump and injection beams are preferably generated by the same chirped-pulse-amplification laser by use of a beamsplitter, which is placed either before or after the final laser compressor. In the former case, the pulsewidths of the injection beam and pump beam could be made to be different from each other by using different compression ratios. Preferably, a cylindrical lens is used in the path of the injector pulse to tightly focus the injection beam in one dimension (along z axis) and loosely along the perpendicular to the plane of incidence formed by the two beams (x). The injection beam's dimension along this later (x) direction could be made to match that of the pump beam spotsize. The injection beam's intensity gradient would thus be large along z but not x, which minimizes the emittance of the accelerated electron beam. The pump beam is preferably loosely focused with a circular lens such that the plasma wave is as one dimensional (1-D) as possible. Information on the accelerated electron energy spectrum is preferably monitored with a magnetic spectrometer and fed back to the laser-delay system in order to optimize the electron beam parameters.

Electrons accelerated by the method of the invention, achieve an energy exceeding 10 MeV in a distance less than a millimeter, as compared to several meters in the case of conventional photocathode electron guns. This reduction in length results in a large reduction in the emittance growth, and thus increases the final-focus luminosity. By eliminating the need for a separate conventional injector, this technique also significantly reduces the complexity of electron accelerators. This is because it is considerably easier to temporally and spatially overlap two laser beams than a laser beam and an electron beam. Femtosecond synchronization between the electron bunch and a single-plasma-wave-acceleration bucket is now made possible with this technique. In another embodiment, the invention is used to study the physics of electron acceleration by wakefield plasma waves. In this embodiment, the delay between pump and injection pulses is varied and then the trapped electron energy gain is monitored to obtain detailed information on both the plasma wave amplitude (as a function of space or time) and the conditions required for trapping. In still another embodiment, a second injection laser pulse counterpropagating to the pump pulse is used to Compton scatter from the accelerated electron beam in order to create high-energy ($4\gamma^2$ hv) photons. This forms the basis for a compact source of ultrashort 10-KeV x-rays.

System Description

An example of an experimental set-up for the laser-injector laser accelerator of the invention is shown in FIG. 4. The major components of the system are laser apparatus (200), vacuum target chamber (210), and electron spectrometer (220). Laser system (200) is preferably a chirped pulse amplification system, CPA system (200). The basic configuration of a CPA system used in the invention will be described more particularly below. The beam of laser light (250) generated from CPA laser (200) is split by beamsplitter mirror (260) into a first pulse (270) which is also referred to as a pump pulse and a second pulse (275) which is referred to as an injection pulse. Pump pulse (270) is directed by mirror (280) through focusing lens (290), preferably, a circular lens. Next, pump pulse (270) is directed to a delay line (300) which is composed of a number of reflective surfaces (305) and then directed onto target (310). Target (310) is any material. Preferably it is a gas, supplied as a jet of gas. As shown in FIG. 4, injection pulse (275) is directed by mirrors (315) onto parabolic lens (320). Lens (320) is preferably a cylindrical lens. Other lenses, such as spherical, may also be used. In the case of a cylindrical lens, the pump pulse (270) causes the plasma wave which has an axial extent (z dimension) and a radial extent (y dimension) and the injection pulse is focused onto the plasma wave by focusing means which provides a beam spot size having a dimension along the y axis which is greater than the size along the z axis. Preferably, the injection pulse is focused onto the plasma wave by focusing means which provides a beam spot size, which in one dimension substantially corresponds to the radial extent of the plasma wave, and in another dimension corresponds to about one plasma wave wavelength (λ_p). Injection pulse (275) is then disposed into beam dump (325). It is desirable to have pump pulse (270) arrive at target (310) first. Injection pulse (275) may arrive at target (310) during the time of pump pulse (270). Preferably, the two pulses (270), (275) are offset with respect to one another, the pump pulse (270) being ahead of the injection pulse (275). In short, the injection pulse (275) is delayed with respect to the pump pulse (270). If desired, the wavelength of the injection and/or pump pulse may be altered by passing through a frequency doubling or tripling crystal (2θ, 3θ) or by optical parametric amplification. The crystal (C) and the λ/4 wave plate circular polarizer (CP) are respectively shown in FIG. 4.

In the method of the invention, laser pulses are used having laser pulse width in the nanosecond to femtosecond range using a chirped pulse amplification (CPA) laser system. The basic configuration of such a CPA system is described in U.S. Pat. No. 5,235,606. U.S. Pat. No. 5,235,606 is incorporated herein by reference in its entirety.

Chirped pulse amplification systems can be roughly divided into four categories. The first includes the high energy low repetition systems such as ND:glass lasers with outputs of several joules but they may fire less than 1 shot per minute. A second category are lasers that have an output of approximately 1 joule and repetition rates from 1 to 20 hertz. The third group consists of millijoule level lasers that operate at rates ranging from 1 to 10 kilohertz. A fourth group of lasers operates at 250 to 350 kilohertz and produces a 1 to 2 microjoules per pulse. In U.S. Pat. No. 5,235,606 several solid state amplifying materials are identified and the invention of U.S. Pat. No. 5,235,606 is illustrated using the Alexandrite. Ti:Sapphire is also commonly used in the basic process of U.S. Pat. No. 5,235,606 with some variations as described below. Other laser means include glass, LiSAF, dyes, LiCAF, and the like.

The illustrative examples described below generally pertain to laser pulse energies in the 1 joule (J) to 5 joule (J) range with pulse width in the range of 100 fs (femtoseconds) to 1 ps (picoseconds) and the wave length on the order of 1 micron (μm). But these examples are merely illustrative and the invention is not limited thereby.

In a basic scheme for CPA laser (410) of FIG. 5, an ultrahigh peak power pulse (411) is produced. First a short pulse (412) is generated. Ideally the pulse (412) from the oscillator (413) is sufficiently short so that further pulse compression is not necessary. After the pulse is produced it is stretched in a stretcher (414) comprising mirrors and gratings arranged to provide positive group velocity dispersion. The amount the pulse is stretched depends on the amount of amplification. A first stage of amplification typically takes place in either a regenerative or a multipass amplifier (415) which is pumped by laser (417). In one configuration this consists of an optical resonator that contains the gain media, a Pockels cell, and a thin film polarizer. After the regenerative amplification stage the pulse can either be recompressed or further amplified. The compressor (416) consists of a grating or grating pair arranged to provide negative group velocity dispersion. Gratings used in the compressor are designed, constructed, and arranged to cooperate with those in the stretching stage. More particulars of a typical system are described in U.S. Pat. No. 5,235,606, previously incorporated herein by reference.

System Modeling

As can be seen, the Laser-Injector Laser ACcelerator (LILAC) of the invention is a stand-alone, desktop-scale, and cost effective electron accelerator which uses two ultrashort and ultraintense laser pulses; the first pulse to generate the highly acceleration efficient electron plasma wave (EPW) and the second one to accelerate a portion of the background electrons (in the PW) supporting the EPW. While not wishing to hold to any particular theory, the model which describes the physics of the LILAC is thought to be as follows. The LILAC mainly consists of three different stages of the acceleration process. The first one is the formation of acceleration medium (plasma wave) by a pump pulse by Laser Wakefield Accelerator (LWFA) to generate EPW in a z direction. The pertinent variables are listed below:

a_0^2: normalized pump laser pulse intensity

Φ: EPW amplitude

ω: laser frequency

ω_p: EPW frequency

Then, $\Phi=f(a_0^2)$. This EPW follows a phase relationship as shown in FIG. 6, between potential, fluid velocity, and electric field, so that background electrons can't be accelerated by their own plasma electric field, except when the plasma wave is very large. Note that velocity and electron potential are out-of-phase in FIG. 6. The second laser pulse (injection pulse) is injected into EPW perpendicular (orthogonal) to the direction of a_0 (y direction for convenience). The pertinent variables are listed below:

b_0^2: normalized injection laser pulse intensity

r_0: spot size of the injection pulse

Z_i: position of the center of laser pulse in z axis

The ponderomotive force of b_0 in z direction dephases the velocities of a group of the EPW background electrons. This concept is shown in FIG. 7 where the electrons are dephased with respect to the plasma wave are illustrated (Curve B). Such electrons dephased with respect to the plasma wave come under the influence of the electric field. As a result of the electron velocity dephasing, EPW electric field, now in-phase with the dephased velocities, accelerates those electrons above the injection threshold for trapping. Finally, those electrons catch up with the plasma wave and are trapped. Electrons in-phase (undephased) are shown in curve A, for comparison.

The LILAC mainly consists of three different stages of the acceleration process. This concept is shown in FIG. 8. The non-relativistic ponderomotive force is defined beginning with Equation 3.1 of Table I, where e is electric charge, μ is normalized velocity, ω is laser frequency, E is electric field of laser, χ0 is a positioning coordinate (axis), and m_0 is rest mass of electron. The relativistic ponderomotive force is given by Equation 3.2 of Table I, and the μ, normalized velocity, is given in Equation 3.3 of Table I, and alternatively, λ^2 is expressed in Equation 3.4 of Table I. In Equation 3.4, the laser wavelength, λ, is in micron and the laser intensity, I, is expressed in W/cm^2. It thus follows that μ^2=0.4 for I=10^{18} W/cm^2 and λ=1 μm (micron). The relativistic corrective effect of ponderomotive force is to reduce the force down to 20 percent lower than the non relativistic version. To compute ΔE^2 first normalized E as per Equation 3.5 and 3.6 of Table I where A is the vector potential. Assume a is the functional form of light pulse as in Equation 3.7 and the square wave envelope and the oscillating portion are given in Equations 3.8 and 3.9, with i being an imaginary number. For relativistic pulse shape in time, replace SQ(t;T, τ) by GS(t;T.τ) which is defined as the Gaussian profile in Equation 3.10. Since ponderomotive force is a time averaged effect, the OSC(t;ω) will drop out of the expression for F_p and the resulting ponderomotive force from the above set of equations is F=F(μ)=F(μ(a)); as per Equation 3.11. The maximum ponderomotive force occurs at $Z-Z_i$ as per Equation 3.12, causing Equation 3.11 to reduce to Equation 3.13. The momentum increase of the background electrons with mass m_0 can be written as in Equations 3.14–3.16 with the variables as defined below:

γ_0: the relativistic factor of background electrons

T: the time or arrival of the injection pulse

τ: the pulse width of the injection pulse

Thus, T is the time when the ponderomotive interaction between injection pulse and electron begins and T+τ the time when it ends.

As to velocity phase drag, define the phase $\Phi=\omega_p t$, then the proportionality is expressed as per Equation 3.17, where the phase of v is chosen as per Equation 3.18. Now v describes the velocity of the background electrons where v_m is the maximum velocity that background electrons attain during the excursion. Denoting phases Φ_1, Φ_2 as per Equations 3.19 and 3.20, it is determined that without injection, velocity evolves from T to T+τ according to Φ only. There is no phase drag for velocity as per Equation 3.21. In

contrast, with injection, an additional term, ponderomotive force, is introduced thus producing phase drag for velocity as per Equation 3.22. With injection, the background electrons which have interacted with the injection pulse will have a phase drag of velocity oscillation compared to others which have not. The amount of this phase delay can be computed as per Equations 3.23–3.28, where Φ_3 is the phase value of unperturbed $v(\Phi)$ which gives the same velocity perturbed at $t=T+\tau$, and Equation 3.23 can be rewritten as Equation 3.24; which is equivalent to Equation 3.25, and yields Equation 3.26. As can be seen in FIG. **10**, the phase delay, δ is as per Equation 3.27, and δ is calculated by Equation 3.28.

To analyze the trapping threshold, the LILAC is reviewed in moving frame of EPW. In FIG. **9**, the velocity dephasing method is described by comparing the motion of an unperturbed background electron and a laser injected electron in the moving frame of reference. It can be understood that the ponderomotive force accelerates the electron while it is on its way down to the valley of the potential. The most general trapping condition is in the moving frame of EPW as per Equation 4.29 with variables as defined below:

ϕ': electric potential of EPW

γ': relativistic factor of the background electron

The quantities have Lorentz and inverse Lorentz transformation property as per Equations 4.30–4.32. Thus, given the ϕ' at the time $T+\tau$, one can compute the minimum value of injection kinetic energy of the particle, $(\Gamma-1)\,m_0c^2$ where Γ is defined as per Equation 4.33 and where ϵ is defined as per Equation 4.34. The formation of LILAC depends on whether a background electron is dephased in velocity so that the δ exceeds the Γ in Equation 4.33. The phase delay in velocity δ is the most relevant quantity for determining the trapping of that particular electron since the plasma wave potential and electric field is not severely modified by the injection pulse. In FIG. **10**, the concept of the phase delay in velocity is introduced graphically. Since $\Phi=\omega_p t$, one derives Equation 4.35. The relativistic factor γ', which is a function of the velocity of the electron which has already been dephased by δ, should also have a phase delay of δ as per Equation 4.36. Following the definition of the trapping condition, one concludes that a background electron will be trapped if ϕ'_{inj}, γ'_{inj}, and $e\phi'_{inj}$ meet criteria as per Equations 4.37 to 4.39. Assuming $v=v_m\Im(e^{i\Phi})$, the phase relationships yield a phase convention for ϕ, as per Equation 4.40, and Equation 4.37 is equivalent to saying that in the lab frame ϕ_{inj} is equal to the values given in Equations 4.41 to 4.43. Equation 4.38 is equivalent to saying that in the lab frame γ_{inj} is as per Equations 4.44 and 4.45, where $v(\Phi_3)$ is derived as per Equations 4.46 and 4.47. Since δ is a function of T, τ and b_0^2 defined in Equation 3.28 then, Equation 4.39 determines Γ, ϵ_{inj}, and γ_{inj} as per Equations 4.48 to 4.50. In order to solve Equations 4.43, 4.45, 4.47, 4.48, 4.50, and 4.51 for injection threshold vale of b_0, rewrite Equation 4.45 as per Equation 4.52. Then, plug Equation 4.52 into Equation 4.51 to get Equation 4.53 and solve Equation 4.53 for F_p, ponderomotive force, as per Equation 4.54 and assuming $F_p=(F_p)_{max}$ in Equation 3.13, rewrite Equation 4.54 as per Equation 4.55. To express v_m in terms of ϵ_{max}, note that by 1-D nonlinear fluid theory, the velocity of the background electrons in EPW has the following relationship with the normalized electric potential

$$E=\frac{e\phi}{m_0c^2}.$$

It is thus possible to use Equations 4.56 and 4.57 and rearrange Equation 4.55 to give the expression for the injection threshold of b_0 given r_0, T, τ, and all the other parameters as per Equation 4.58. Equations 4.33 and 4.58 are referenced in a paper by T. Katsoulears et al., UCLA, PPG-854 (1985) Equation 4.58 together with Equations 4.48 and 4.50 determines the approximate value of b_0 for LILAC operation.

TABLE I

$$\vec{F}_p=-\frac{e^2}{4m\omega^2}\nabla\vec{E}^2(\vec{x}) \tag{3.1}$$

$$\vec{F}_p=\begin{cases}\dfrac{1}{\sqrt{1+\mu^2}}\ \dfrac{m_0c^2}{2}\nabla\mu^2, & \text{(circular polarization)}\\[2ex] \dfrac{1}{\sqrt{1+\mu^2}}\ \dfrac{m_0c^2}{4}\nabla\mu^2, & \text{(linear polarization)}\end{cases} \tag{3.2}$$

$$\mu^2=\frac{e^2\vec{E}^2}{m_0^2c^2\omega^2} \tag{3.3}$$

$$\mu^2=\frac{n_0\lambda^2 l}{\pi m_0c^3}=4\times10^{-19}\lambda^2 l \tag{3.4}$$

$$\vec{A}=\frac{m_0c}{e}\vec{a} \tag{3.5}$$

$$\vec{E}=\frac{\partial\vec{A}}{\partial t}=\frac{-m_0c}{e}\omega\vec{a} \tag{3.6}$$

$$\vec{a}=\vec{b}_0\times\exp\left[-\left(\frac{z-z_i}{r_0}\right)^2\right]\times SQ(z,T,\tau)\times OSC(z,\omega) \tag{3.7}$$

$$SQ(z,T,\tau)=\begin{cases}1, & \text{if } t<T+\tau, \text{ and } t>T\\ 0, & \text{otherwise}\end{cases} \tag{3.8}$$

$$OSC(z,\omega)=e^{ikz} \tag{3.9}$$

$$GS(z,T,\tau)=\exp\left[-\left(\frac{z-T-\tau/2}{\tau/2}\right)^2\right] \tag{3.10}$$

$$F_p(z,t)=b_0^2\frac{m_0c^2}{\sqrt{1+\mu^2}}\left(\frac{z-z_i}{r_0}\right)\times\exp\left[-2\left(\frac{z-z_i}{r_0}\right)^2\right]\times\begin{cases}SQ(t)\\ GS(t)\end{cases} \tag{3.11}$$

$$z-z_i=r_0/2 \tag{3.12}$$

$$(F_p)_{max}=b_0^2\frac{m_0c^2}{r_0}\ \frac{\exp(-1/2)}{2\sqrt{1+\mu^2}} \tag{3.13}$$

$$\Delta p = \gamma_0 m_0\Delta v \tag{3.14}$$

$$= \int_T^{T+\tau}F_p(t)dt \tag{3.15}$$

$$= F_p\tau(\text{for Super-wide pulse}) \tag{3.16}$$

$$v,\ \phi,\ E\propto e^{ikz} \tag{3.17}$$

$$v=\Im(v_m e^{i\Phi_3}) \tag{3.18}$$

$$\Phi_3=\omega_p T \tag{3.19}$$

TABLE I-continued

$$\Phi_2 = \omega_p(T+\tau) \tag{3.20}$$

$$u(\Phi_1) \rightarrow u(\Phi_2) \tag{3.21}$$

$$u(\Phi_1) \rightarrow u(\Phi_2) + \Delta u \tag{3.22}$$

$$u(\Phi_2) + \Delta u = u(\Phi_3) \tag{3.23}$$

$$\Im(u_m e^{i\Phi_2}) + \Delta u = \Im(u_m e^{i\Phi_3}) \tag{3.24}$$

$$u_m \sin\Phi_2 + \Delta u = u_m \sin\Phi_3 \tag{3.25}$$

$$\Phi_3 = \sin^{-1}\left(\sin\Phi_2 + \frac{\Delta u}{u_m}\right) \tag{3.26}$$

$$\delta = \Phi_2 - \Phi_3 \tag{3.27}$$

$$\delta = \Phi_2 - \Phi_3 = \Phi_2 - \sin^{-1}\left(\sin\Phi_2 + \frac{\Delta u}{u_m}\right) \tag{3.28}$$

$$e\phi' \geq (\gamma' - 1)m_0c^2 \tag{4.29}$$

$$\phi' = \gamma_0\phi \tag{4.30}$$

$$\gamma' = \gamma_0\gamma(1 - \beta_0\beta) \tag{4.31}$$

$$\gamma = \gamma_0\gamma'(1 + \beta_0\beta') \tag{4.32}$$

$$\Gamma - 1 = \gamma_0^2\{\epsilon + 1/\gamma_0 - \beta_0(\epsilon + 2/\gamma_0)\epsilon^{1/2}\} - 1 \tag{4.33}$$

$$\epsilon = \frac{e\phi}{m_0c^2} \tag{4.34}$$

$$\phi'(T+\tau) = \phi'(\Phi_2) \tag{4.35}$$

$$\gamma'(T+\tau) = \gamma'(\Phi_2 - \delta) = \gamma'(\Phi_3) \tag{4.36}$$

$$\phi'_{inj} = \phi'_{max} - \phi'(\Phi_2) \tag{4.37}$$

$$\gamma'_{inj} = \gamma'(\Phi_3) \tag{4.38}$$

$$e\phi'_{inj} \geq (\gamma_{inj} - 1)m_0c^2 \tag{4.39}$$

$$\phi = \phi_{max}\Im(e^{i\Phi+i\pi}) = -\phi_{max}\sin\Phi \tag{4.40}$$

$$\begin{aligned}\phi_{inj} &= \phi_{max} - \phi(\Phi_2) \\ &= \phi_{max}(1 + \sin\Phi_2) \\ &= \phi_{max}(1 + \sin\omega_p(T+\tau))\end{aligned} \tag{4.41}$$

$$\begin{aligned}\gamma_{inj} &= \gamma(\Phi_3) \\ &= \frac{1}{\sqrt{1 - \frac{u(\Phi_3)^2}{c^2}}}\end{aligned} \tag{4.44}$$

$$\begin{aligned}u(\Phi_3) &= u(\Phi_2 - \delta) = u(\omega_p(T+\tau) - \delta) \\ &= u_m\sin\omega_p(T+\tau) + \frac{F_p\tau}{\gamma_0 m_0}\end{aligned} \tag{4.46}$$

$$\Gamma = \gamma_0^2\{\epsilon_{inj} + 1/\gamma_0 - \beta_0(\epsilon_{inj} + 2/\gamma_0)\epsilon_{inj}^{1/2}\} \tag{4.48}$$

$$\begin{aligned}\epsilon_{inj} &= \frac{e\phi_{inj}}{m_0c^2} \\ &= \frac{e\phi_{max}(1 + \sin\omega_p(T+\tau))}{m_0c^2}\end{aligned} \tag{4.49}$$

$$\gamma_{inj} \geq \Gamma \tag{4.50}$$

$$\gamma_{inj} = \frac{1}{\sqrt{1 - \frac{1}{c^2}\left(u_m\sin\omega_p(T+\tau) + \frac{F_p}{\gamma_0 m_0}\tau\right)^2}} \tag{4.51}$$

TABLE I-continued

$$1 - \frac{1}{c^2}\left(u_m\sin\omega_p(T+\tau) + \frac{F_p}{\gamma_0 m_0}\tau\right)^2 \leq \frac{1}{\Gamma^2} \tag{4.53}$$

$$F_p \geq \frac{\gamma_0 m_0}{\tau}\left(c\sqrt{1 - \frac{1}{\Gamma^2}} - u_m\sin\omega_p(T+\tau)\right) \tag{4.54}$$

$$b_0^2 \frac{m_0c^2}{r_0} \frac{\exp(-1/2)}{2\sqrt{1+\mu^2}} \tag{4.55}$$

$$\geq \frac{\gamma_0 m_0}{\tau}\left(c\sqrt{1 - \frac{1}{\Gamma^2}} - u_m\sin\omega_p(T+\tau)\right)$$

$$\beta = \frac{1 - (1+\epsilon)^2}{1 + (1+\epsilon)^2} \tag{4.56}$$

$$u_m = c\left|\frac{1 - (1 + \epsilon_{max})^2}{1 + (1 + \epsilon_{max})^2}\right| \tag{4.57}$$

$$b_0^2 \geq 2\frac{r_0}{cr}\frac{\gamma_0\sqrt{1+\mu^2}}{\exp(-1/2)}\left(\sqrt{1 - \frac{1}{\Gamma^2}} - \left|\frac{1 - (1 + \epsilon_{max})^2}{1 + (1 + \epsilon_{max})^2}\right|\sin\omega_p(T+\tau)\right) \tag{4.58}$$

In order to test the model of the method, a simulation of single particle in two dimension was performed. The relativistic equation of motion was solved to follow the trajectory of a trapped electron in the phase space. The codes validity was tested using the ponderomotive force of the injection pulse and the trapping of an electron in the plasma wave, to see if they are consistent with the motion expected.

In FIG. 11, the final drift velocity along the direction perpendicular to the propagation of the injection pulse is shown as a function of the injection pulse amplitude. Gaussian shape for injection pulse spotsize and width is chosen. The electron starts at rest at t=0, a distance $r_0/2$ away from the center of the injection pulse. It is accelerated to the final drift velocity as the pulse passes by. $r_0/2$ was chosen since that is where the ponderomotive force is maximum. (π is pi and e is natural number, log scale.) Thus, the curve represents:

$$(\gamma\beta)_{\phi\phi} = \frac{b_0^2}{\sqrt{1 + b_0^2/2}}\sqrt{\pi/8}e^{-1/2},$$

The points plotted out in the figure represents the simulations and the agreement is well established except at high values of b_0. The deviation has come from the fact that the amplitude of the ponderomotive force in the curve is always calculated at the $z=r_0/2$. With a high value of b_0, the z displacement of the particle is prominent and the maximum ponderomotive force assumption holds true no longer.

In FIG. 12, the trapping formula, Equation 4.33 is plotted and using the same simulation trapping is observed for waves of various amplitude. The points represent the fact that the electron with an initial and an initial position at the maximum of electric potential would be trapped.

Observing that the code produced the agreeable results on the tests for ponderomotive force and trapping, it is possible to link the two curves since the final drift velocity that can be obtained from the ponderomotive force is used to inject electrons into the plasma wave. In FIG. 13, the drift and the injection velocity are coupled so that the energy coming from the ponderomotive drift gives a trapping threshold curve in terms of b_0. The solid line represents the curve that

can be obtained from coupling the trapping and the drifting velocity formula directly. The explicit form of this curve is:

$$b_0 = \sqrt{\chi^2/4 + \sqrt{\chi^4/16 + \chi^2}} \quad ,$$

where

$$\chi = \sqrt{8/\pi e^{1/2}} \quad \sqrt{\Gamma^2 - 1}$$

The dotted line is the numerical solution of the same model. The discrepancy occurs between the above expression and the numerical solution because of approximations needed to solve for an analytic expression of the drift velocity. The rectangular points are from the simulation. They show the same tendency of the other two curves, though they do not agree with the ponderomotive drift model. The physical interpretation of this is simple, the larger the plasma wave amplitude becomes, the easier it is to trap the electron. There is still some disagreement between the predicted and the simulated results. This is because there were several approximations in order to make the FIG. 13. The plot was made as if the electron is pre-accelerated only by the ponderomotive force of injection pulse without the influence of the plasma wave. In reality, the electrons will be accelerated within the plasma wave electric field and the phase of the injected electrons with respect to the plasma wave will account for the discrepancy between the simulation points and the predicted curve in FIG. 13.

It was determined that it is necessary to match the velocity of the electron to the phase velocity of the wave for the electron to gain energy from the plasma wave. The phase velocity of the plasma wave is about the speed of light, almost C. An electron at C has energy of about an MeV. Therefore, it is necessary to impart to the electron a change in momentum such that it will end up with that final velocity while it is still in the region where it comes under the influence of the electric field for acceleration by the plasma wave. The intensity necessary to do this corresponds to a gain in energy equal to the rest mass of the electron which is about an MeV, and the energy required is approximately 10^{18} W/cm^2 (watts per square centimeter) for 1 μm (micron).

As an example of the principle, a simulation of one possible configuration was performed. The simulation used is of a type known as Particle-in-Cell or PIC. This type of numerical simulation is common in plasma physics, especially in situations where analytic solutions are impossible. Particles representing free electrons and atomic ions move within the confines of a spatial grid under the influence of electric and magnetic fields. The particular PIC code used has one spatial dimension, z, and velocities in three dimensions, x, y, and z. The motion of the particles is calculated using fully relativistic equations of motion for a charged particle in electromagnetic fields. The fields are solved self-consistently for the initial condition and then evolve temporally according to Maxwell's equations.

The chosen characteristics for the simulation are that of a three pulse configuration. There are two pump pulses and a single injection pulse. The first pump drives up the wave while the second identical pump follows the first at a distance of 3/2 the wavelength of the wake in order to drive the wave back down. This creates only a small region for trapping so that the electron beam is very short. The two pump pulses have a laser wavelength of 1 μm (micron) and a length equal to the wavelength of the wake, 10 μm (microns), or 33 femtoseconds. Their normalized intensity is a_0=1.00. The pump pulse has a length equal to 3 times the length of one of the pump pulses, and its intensity twice that of the pumps, $b_0=2a_0=2.00$. The spotsize of the injection pulse is r_0=5 μm (microns), and the position is such that the peak of the injection pulse crosses the axis of the pump pulses one plasma wavelength behind the peak of the first pulse.

The results of the simulation are summarized in three plots. The first, FIG. 14, is a plot of the wave propagating through the plasma, in the frame of the moving wave. The four quantities plotted are: the laser intensity, a_0; the electric field of the wake,

$$\frac{eE}{m_e c \omega_p} ;$$

the electric potential,

$$\frac{e\phi}{m_e c^2} ;$$

and the individual particle velocities, β_z. The first three qualities are noted on the plot's legend. The velocities are plotted as individual points on the plot. It is clear that after the second pump pulse there is no wake. The particles trapped in the wave forming the beam are centered around 37 fs (femtoseconds). The amplitude of the wave matches the expectation from theory explaining the formation of wakes. FIG. 15 demonstrates the trapping of the particles in the wave. This time normalized momenta of the particles, $\gamma\beta_z$, are plotted. The solid line represents the trapping condition of Equation 4.33, based on the electric potential of the wave. Any particle with a momentum above this line is then trapped in the wave. Again, at about 37 fs (femtoseconds) the trapped particles can be seen, well above the trapping condition. The phase velocity of the wave is $\gamma\beta$=10, so the particles are actually moving faster than the wave at this point. The third plot, FIG. 16, shows the energy spectrum of the electrons at the end of the simulation. They fall into two groups, the first is the background electrons with energies ranging from 0 to 1 MeV. The second group centered at 5 MeV, are the electrons in the beam. The plot shows a distinct separation of the beam from the background, with a small energy spread in the injected beam, about 10 percent.

While this particular simulation may not be optimized for the best possible configuration, it does show one possible configuration. It also demonstrates the robustness of this technique, that a beam of excellent quality, small energy spread, can be created even under non-optimal conditions; optimal yet to be determined.

The method and apparatus of the invention are unlike other plasma-based accelerators, which are exclusively second-stage high-energy electron accelerators, requiring a trailing bunch of electrons that have been generated and pre-accelerated in a conventional combination electron gun and linear accelerator (linac).

The invention utilizes laser-driven plasma waves as the first-stage low-energy electron gun/linac itself. As such, it forms the basis for a compact (table-top) source of relativistic electrons, that can either be used by itself or as an injector for high-energy accelerators. Electrons are accelerated to relativistic velocities in a distance less than a millimeter as compared with several meters for a comparable conventional linac, resulting in lower beam emittance and a more compact size. It also produces much shorter-duration electron pulses (femtosecond as compared with picosecond). For applications that require an electron bunch synchronized with a laser-light pulse, femtosecond accuracy

may be achieved with the invention. In a preferred embodiment, two orthogonally directed laser beams are injected into a plasma: one beam creates a wakefield plasma wave, and the other alters the trajectory of background electrons in such a way that they become trapped in the plasma wave and are then accelerated to relativistic velocities in a distance less than a millimeter. Compared with a conventional electron linac, the LILAC has a much higher field gradient, resulting in lower beam emittance. Since it also can produce much shorter-duration electron pulses, it can be used for the study of ultrafast dynamics on femtosecond timescales. The invention also enables femtosecond-synchronization between the electron bunch and the plasma wave acceleration field, which is required to achieve a low-energy spread for the accelerated electrons. A high-flux low-emittance beam of 20-MeV electrons can be produced with a currently-available table-top high-intensity laser ($I \leq 1 \times 10^{18}$ W/cm^2). The principle upon which the LILAC is based can be used to study the growth of, and the trapping of electrons in, laser wakefield plasma waves.

In summary, the pulses of the invention are ultra short pulses generated by laser systems as described in FIGS. 4, 5 and 17. In the method of the invention, the pump pulse and the injection pulse may be obtained from the same laser beam by splitting a single laser pulse into two sub-pulses. The beamsplitting may occur before (FIG. 17) or after (FIG. 4) recompression in the laser system, shown schematically in FIG. 5. If such beamsplitting occurs after recompression (FIG. 4), then the pump and injection pulses are synchronized with respect to one another. The invention may also be used with the beamsplitter (FIG. 17) prior to recompression, in order to achieve pump pulse and injection pulse of different pulse time durations. Therefore, FIG. 17 encompasses the elements of FIGS. 4 and 5, and the beamsplitter 502 is arranged between amplified 415 which was previously shown in FIG. 5, and compressors 416(*a*) and 416(*b*), similar to single compressor 416 of FIG. 5. More specifically, in FIG. 17, beam 500 is split by beamsplitter 502 into a first pulse 504 and a second pulse 506. Pulse 504 is directed by mirror 510 to compressor 416(*a*), then by mirror 512 and optics 514 to target 515. Pulse 506 enters compressor 416(*b*) and then enters delay line 516, comprising mirrors 518(*a*), (*b*), (*c*), and (*d*). Next, pulse 506 is directed onto target 515 by optics 520.

While this invention has been described in terms of certain embodiments thereof, it is not intended that it be limited to the above description, but rather only to the extent set forth in the following claims. The embodiments of the invention in which an exclusive property or privilege is claimed are defined in the following claims.

We claim:

1. A method for accelerating electrons comprising: generating a plasma wave in a plasma comprising free electrons and atomic ions, said plasma wave characterized by an electric field; producing dephased electrons that are dephased with respect to said plasma wave; and accelerating said dephased electrons by force of said plasma wave electric field.

2. The method according to claim 1 wherein said dephased electrons are formed by directing a beam comprising at least one laser pulse into said plasma wave to dephase said electrons with respect to said plasma wave.

3. The method according to claim 2 wherein said beam is injected into said plasma wave in a direction different from the direction of propagation of said plasma wave.

4. The method according to claim 2 wherein said laser pulse has an intensity gradient sufficient to alter the trajectory of said free electrons thereby providing said dephased electrons.

5. The method according to claim 2 wherein said dephased electrons are formed from said atomic ions in said plasma by said laser pulse at an intensity sufficient to remove said electrons from said atomic ions thereby providing said dephased electrons.

6. The method according to claim 1 wherein said plasma wave is formed by generating a first beam of at least one pump laser pulse; and directing said pump pulse onto a target to produce said free electrons and atomic ions by photo ionization of said target, and to produce said plasma wave moving in the direction of propagation of said pump pulse.

7. The method according to claim 6 wherein said at least one laser pulse comprises first and second pump laser pulses, said first laser pulse which produces said free electrons and atomic ions, and said second pump laser pulse which produces said plasma wave.

8. The method according to claim 7 wherein said first pulse arrives at said target before said second pulse.

9. The method according to claim 8 wherein said second pulse is delayed with respect to said first pulse for a time sufficient for any plasma wave produced by said first pulse to dampen away.

10. The method according to claim 6 wherein said dephased electrons are produced by generating a second beam of at least one injection laser pulse and directing said injection pulse into said plasma wave, said injection pulse having an intensity sufficient to remove electrons from said atomic ions, thereby providing said dephased electrons.

11. The method according to claim 10 wherein said injection laser pulse has an intensity greater than said pump pulse.

12. The method according to claim 10 wherein said injection laser pulse has an intensity sufficient to remove said electrons from said atomic ions by photo-ionization and to impart to said removed electrons a residual velocity sufficient to cause said electrons to be trapped by said plasma wave.

13. The method according to claim 10 wherein said injection laser pulse removes electrons from said atomic ions at a higher ionization stage than that of said electrons removed by ionization of said target by said pump pulse.

14. The method according to claim 10 wherein said injection laser pulse is collinear with said pump pulse.

15. The method according to claim 10 wherein said injection laser pulse is injected into said plasma wave in a direction orthogonal to the direction of propagation of said pump pulse.

16. The method according to claim 10 wherein said at least one injection laser pulse comprises two injection laser pulses arranged counterpropagating to one another and each directed into said plasma wave at a direction orthogonal to the direction of propagation of said plasma wave to offset any drift of said electrons in a direction transverse to the direction of propagation of said plasma wave.

17. The method according to claim 10 wherein said pump and injection laser pulses are directed into said plasma wave essentially simultaneously.

18. The method according to claim 10 wherein a single pump laser pulse and a single injection laser pulse are used.

19. The method according to claim 10 wherein said injection and pump laser pulses have differing wavelengths.

20. The method according to claim 10 wherein said injection and pump laser pulses have differing pulse widths (pulse time duration).

21. The method according to claim 10 wherein said injection and pump laser pulses have differing polarization.

22. The method according to claim 1 wherein said step of producing said dephased electrons includes altering the position, direction, and velocity of said dephased electrons so as to position said dephased electrons in an optimal region of said plasma wave electric field with a velocity that exceeds the phase velocity of said plasma wave.

23. A method for accelerating electrons comprising the steps of:

a. generating a beam of at least one pump laser pulse;

b. directing said pump pulse onto a target to produce a plasma wave in a plasma comprising free electrons and atomic ions; said plasma wave moving in the direction of propagation of said pump pulse, encompassing electrons in-phase with oscillating motion of said plasma wave, and being characterized by an electric field;

c. generating a beam of at least one injection laser pulse;

d. directing said injection pulse beam into said plasma wave in a direction transverse to the direction of propagation of said plasma wave to produce dephased electrons that are dephased with respect to the oscillating motion of said plasma wave; and

e. positioning said dephased electrons in said plasma wave electric field and accelerating said electrons by force of said electric field.

24. The method according to claim 23 wherein said injection laser pulse has an intensity gradient sufficient to alter the trajectory of said in-phase electrons by ponderomotive force thereby providing said dephased electrons.

25. The method according to claim 23 wherein said pump laser pulse and said injection laser pulse have differing wavelengths, pulsewidths, intensities, and/or polarizations.

26. The method according to claim 25 wherein said differing wavelength is achieved by directing one or both of said injection and pump pulses through an optical device which alters the wavelength prior to directing said pulse onto said target.

27. The method according to claim 23 wherein said dephased electrons are produced from electrons present in atomic ions in said plasma and said injection laser pulse has an intensity sufficient to remove said electrons from said atomic ions by photo-ionization thereby providing said dephased electrons.

28. The method according to claim 27 wherein said injection laser pulse has an intensity sufficient to remove said electrons from said atomic ions by photo-ionization and to impart to said removed electrons a residual velocity sufficient to cause said electrons to be trapped by said plasma wave.

29. The method according to claim 23 wherein said at least one injection laser pulse comprises two injection pulses arranged counterpropagating to one another and each directed into said plasma wave at a direction orthogonal to the direction of propagation of said plasma wave.

30. The method according to claim 29 wherein said two injection pulses are injected into said plasma wave essentially simultaneously.

31. The method according to claim 23 wherein a single pump laser pulse and a single injection laser pulse are used.

32. The method according to claim 31 wherein said injection laser pulse is injected into said plasma wave essentially simultaneously with said pump laser pulse or after said pump laser pulse.

33. The method according to claim 23 wherein said injection laser pulse is focused onto said plasma wave by focusing means which provides a beam spot size, which in one dimension substantially corresponds to the radial extent of the plasma wave, and in another dimension corresponds to about one plasma wave wavelength (λ_p).

34. The method according to claim 23 wherein the plasma wave has an axial extent (z axis) and a radial extent (y axis) and the injection laser pulse is focused onto said plasma wave by focusing means which provides a beam spot size having a dimension along the y axis which is greater than the size along the z axis.

35. The method according to claim 23 wherein first and second pump laser pulses are used, said second pump pulse is generated at an interval of 3/2 plasma wavelengths (3/2 λ_p) after the first pump pulse, to provide an acceleration region of a single plasma wavelength and thus provide a single electron bunch.

36. The method according to claim 23 wherein the pump pulse beam and the injection pulse beam are each produced from a single laser pulse which is split into two pulses, the first being said pump pulse and the second being said injection pulse.

37. The method according to claim 23 wherein one or both of said pump and injection laser pulses is directed through respective optical means which adjusts the arrival time of said pulses at said target relative to one another.

38. The method according to claim 23 wherein said injection laser pulse arrives at said target during said pump pulse.

39. The method according to any one of claims 2, 6, 10, and 23 wherein each of said laser beams is obtained by chirped pulse amplification means comprising means for generating a laser pulse; means for stretching such laser pulse in time; means for amplifying such time-stretched laser pulse; and means for recompressing such amplified pulse.

40. An apparatus for accelerating electrons comprising:

a. a vacuum chamber;

b. laser pulse generating means for generating a beam of one or more laser pulses;

c. a target supported in said chamber, said target comprising matter which forms a plasma upon bombardment by one or more laser pulses;

d. beam splitting means which splits each of said generated laser pulses into two sub-pulses, a first sub-pulse and a second sub-pulse;

e. optical means which delays at least one of said sub-pulses and directs it to said target;

f. first laser focusing means, disposed between said laser generating means and said target, which focuses said first sub-pulse onto said target and adjusts the size of the spot of the beam and its corresponding intensity incident at said target to produce a plasma wave in said plasma;

g. second laser focusing means, disposed between said laser generating means and said target, which focuses said second sub-pulse onto said target and adjusts the size of the spot of the beam and its corresponding intensity incident at said target to provide electrons in said plasma which are out of phase with said plasma wave formed by said first sub-pulse; and

h. said first focusing means and said target arranged in said chamber to define a first path for said first sub-pulse, said second focusing means and said target arranged in said chamber to define a second path for said second sub-pulse which is transverse to the first path.

41. The apparatus according to claim 40 wherein said laser pulse generating means comprises a chirped pulse amplification (CPA) system.

42. The apparatus according to claim 41 wherein said CPA system comprises means for generating an optical pulse, means for stretching the pulse in time, means for amplifying the time stretched pulse including solid state amplifying media, and means for recompressing the amplified pulse.

43. The apparatus of claim 42 wherein said CPA system produces a beam of one or more pulses having an incident intensity of at least about 10^{16} watts per square centimeter at a laser pulse time duration of less than a picosecond.

44. The apparatus according to claim 40 wherein said beam splitting means comprises a transparent substrate with a reflective coating that produces partial transmission.

45. The apparatus according to claim 44 wherein said beam splitting means is arranged between said pulse amplifying means and said recompression means, and said recompression means comprises a first compressor which recompresses said pump pulse and a second compressor which recompresses said injection pulse to a pulse time duration different from said pump pulse.

46. The apparatus according to claim 44 further comprising wavelength adjustment means arranged between said beam splitting means and one of said focusing means.

47. The apparatus of claim 40 wherein said second laser focusing means comprises a cylindrical lens or mirror.

48. The apparatus according to claim 44 further comprising a wave plate circular polarizer arranged between said beam splitting means and said second focusing means.

* * * * *

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United States Patent [19]

Schultheiss et al.

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[45] Date of Patent: Nov. 19, 1996

[54] **APPARATUS FOR ACCELERATING ELECTRICALLY CHARGED PARTICLES**

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[73] Assignee: **Kernforschungszentrum Karlsruhe GmbH**, Karlsruhe, Germany

[21] Appl. No.: **301,078**

[22] Filed: **Sep. 6, 1994**

Related U.S. Application Data

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[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**[6] **H05H 9/00**

[52] **U.S. Cl.** **313/231.31**; 313/361.1; 313/362.1; 250/398; 315/505

[58] **Field of Search** 313/231.31, 360.1, 313/361.1, 362.1; 250/398, 288; 315/505, 507

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Primary Examiner—Sandra L. O'Shea
Assistant Examiner—Matthew J. Esserman
Attorney, Agent, or Firm—Klaus J. Bach

[57] **ABSTRACT**

In an apparatus for accelerating electrically charged particles from a pulsed plasma reservoir of high particle density in a dielectric tubular chamber which extends from the reservoir and is surrounded by at least two electrodes of which one is disposed at the wall of the reservoir, the dielectric tubular chamber is partially evacuated to a sufficiently low pressure p such that the product of the gas pressure p and the inner diameter d of the tubular chamber is low enough to avoid parasitic discharges in the residual gas charge, and a voltage is applied to the electrodes such that the particles are drawn into the dielectric tubular chamber with high flow density and are accelerated therein thereby forming a charged particle beam whereby the residual gas charge in the dielectric tubular chamber is ionized along the inside wall of the tubular chamber and polarized such that the wall of the dielectric tubular chamber becomes repulsive for the charged particle beam and its axis becomes attractive whereby the charged particle beam is electrostatically focussed and exits the dielectric tubular chamber with log losses.

12 Claims, 7 Drawing Sheets

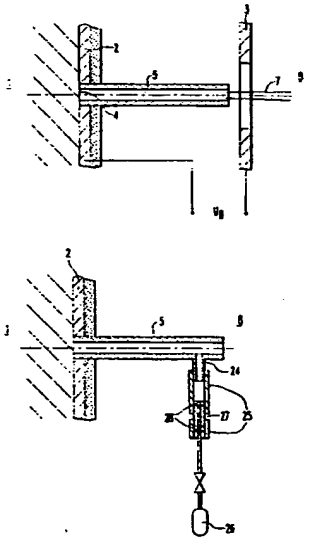


FIG. 1a

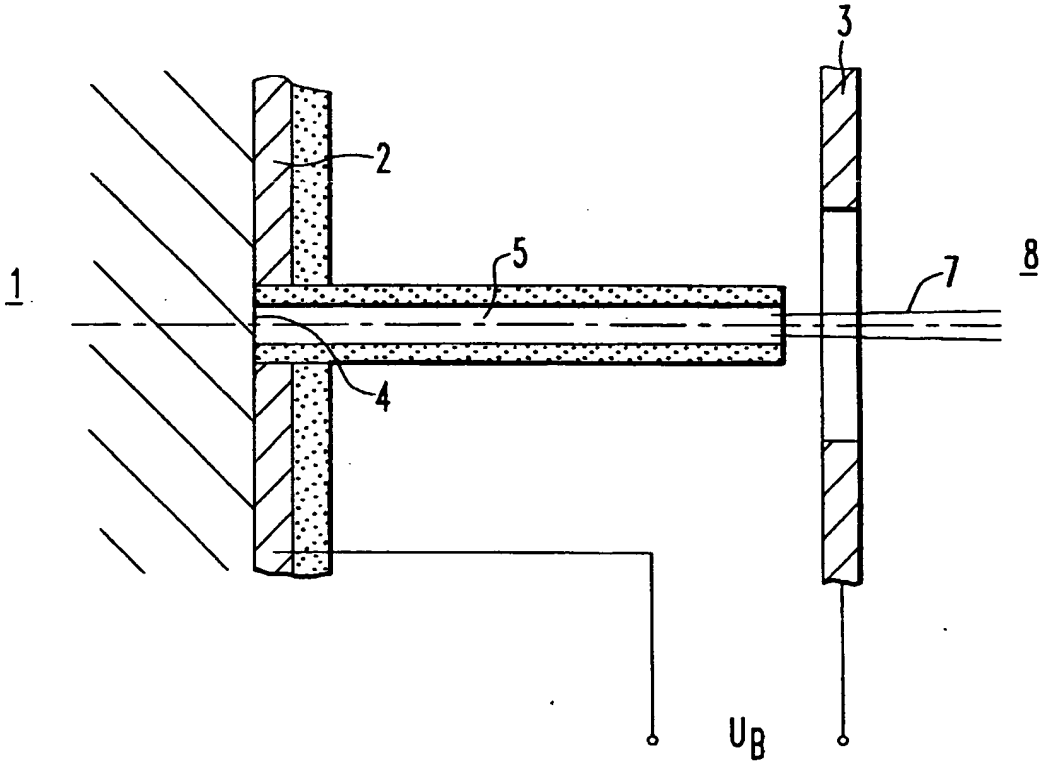


FIG. 1b

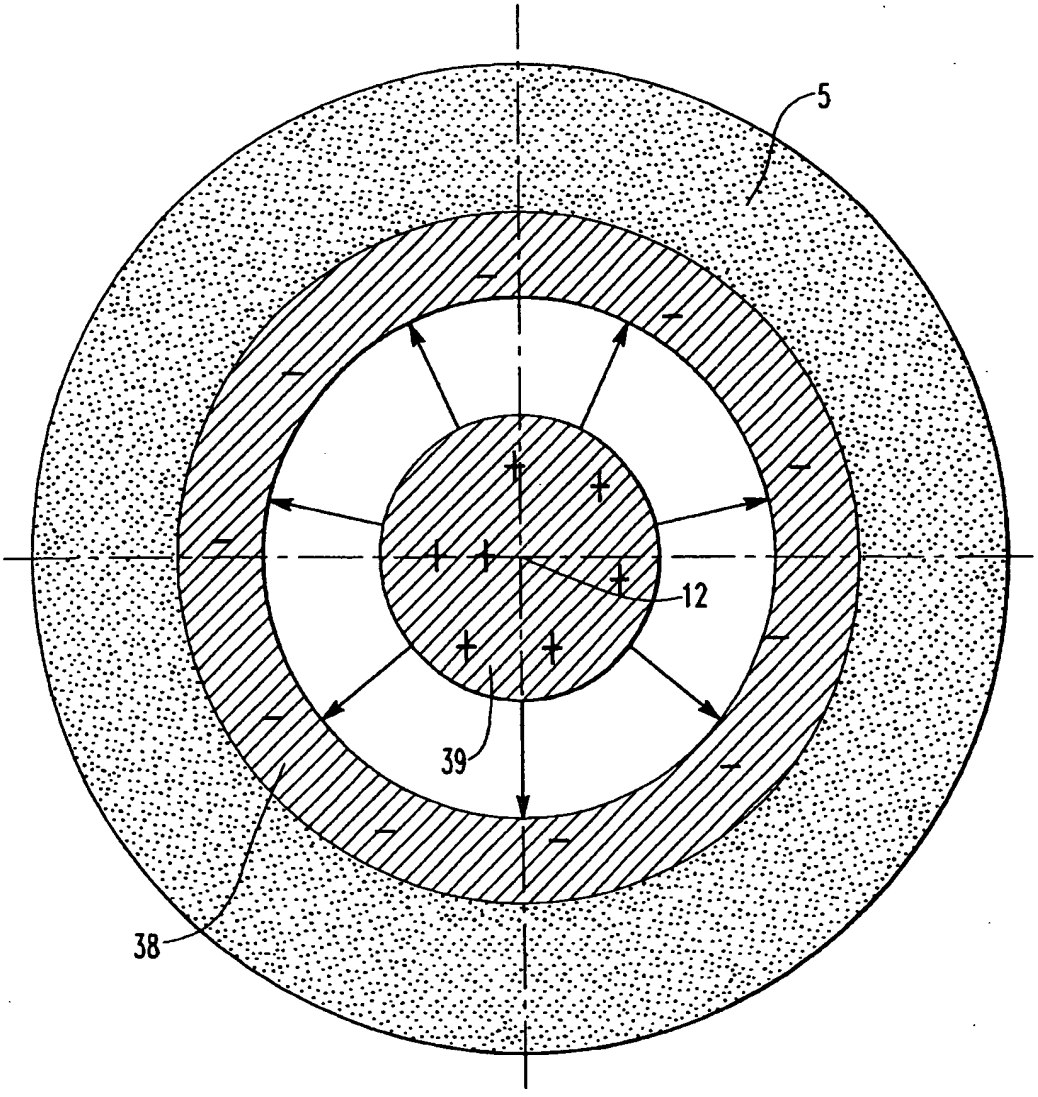


FIG. 2

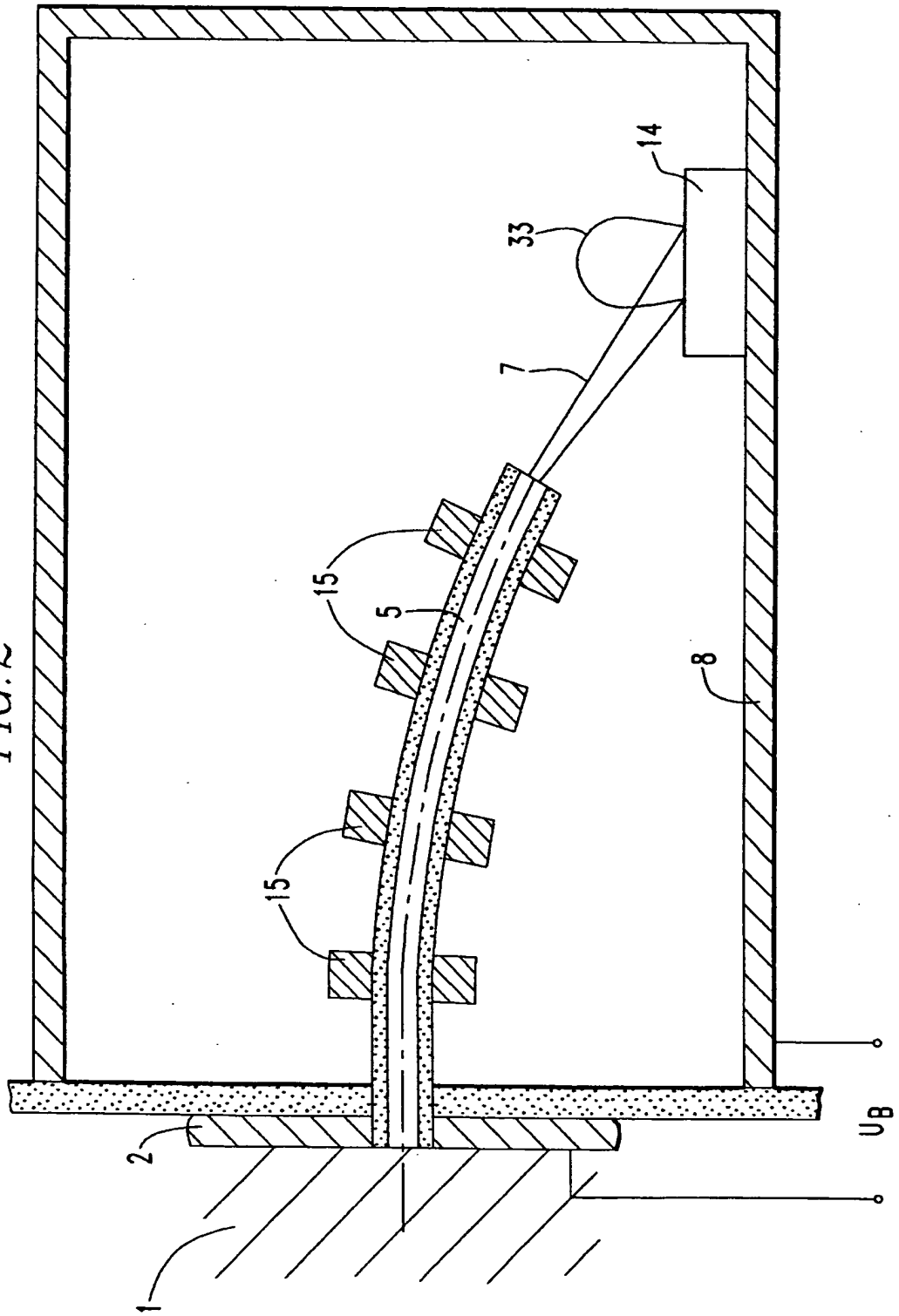


FIG. 3a

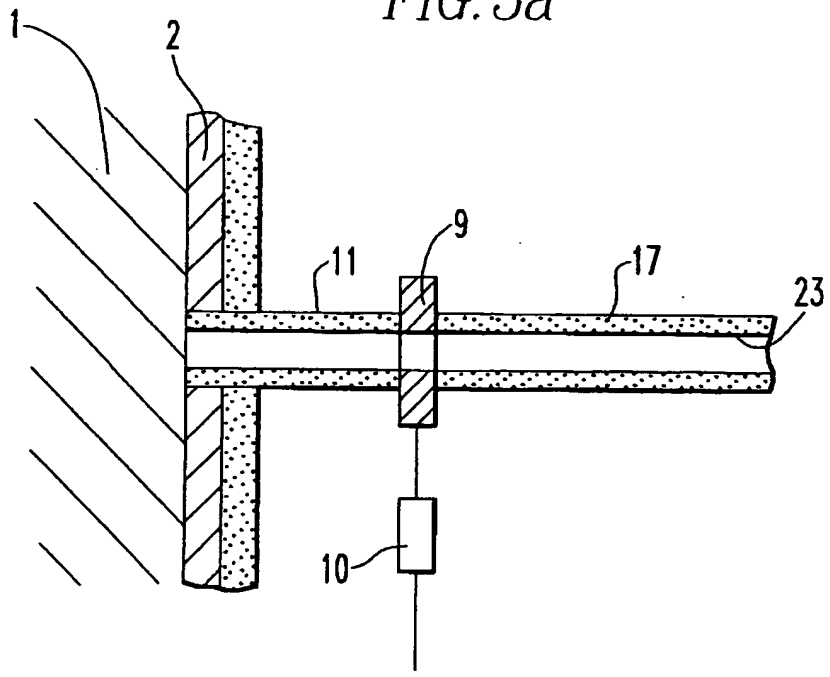
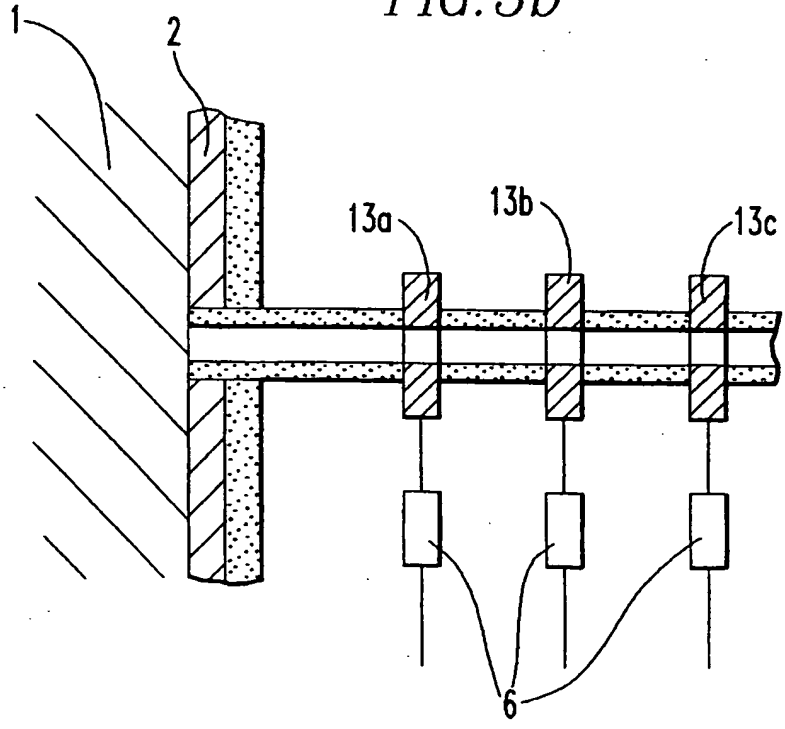


FIG. 3b



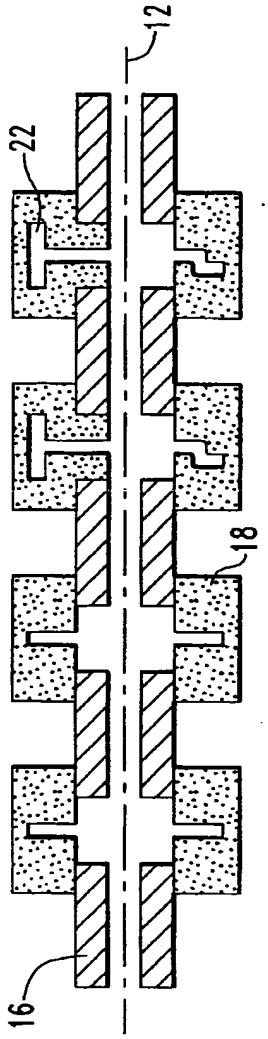


FIG. 4a

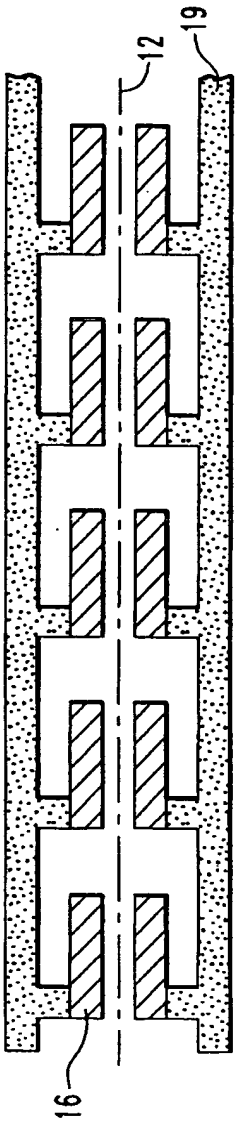


FIG. 4b

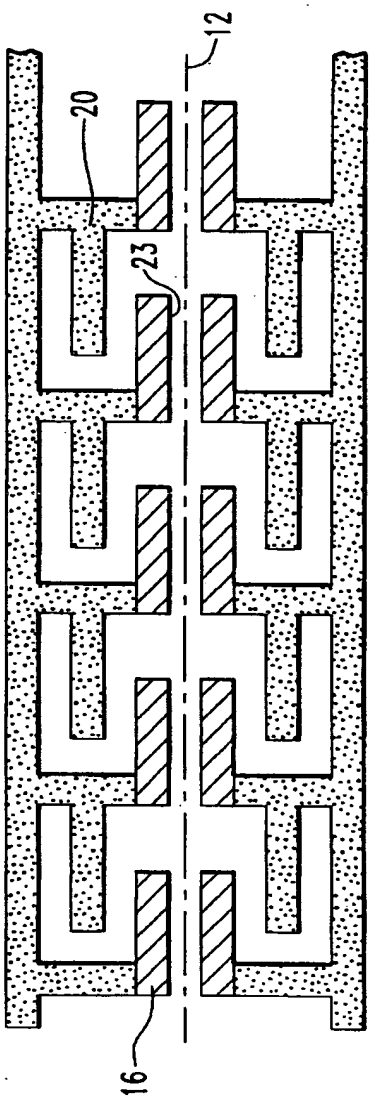


FIG. 4c

FIG. 5

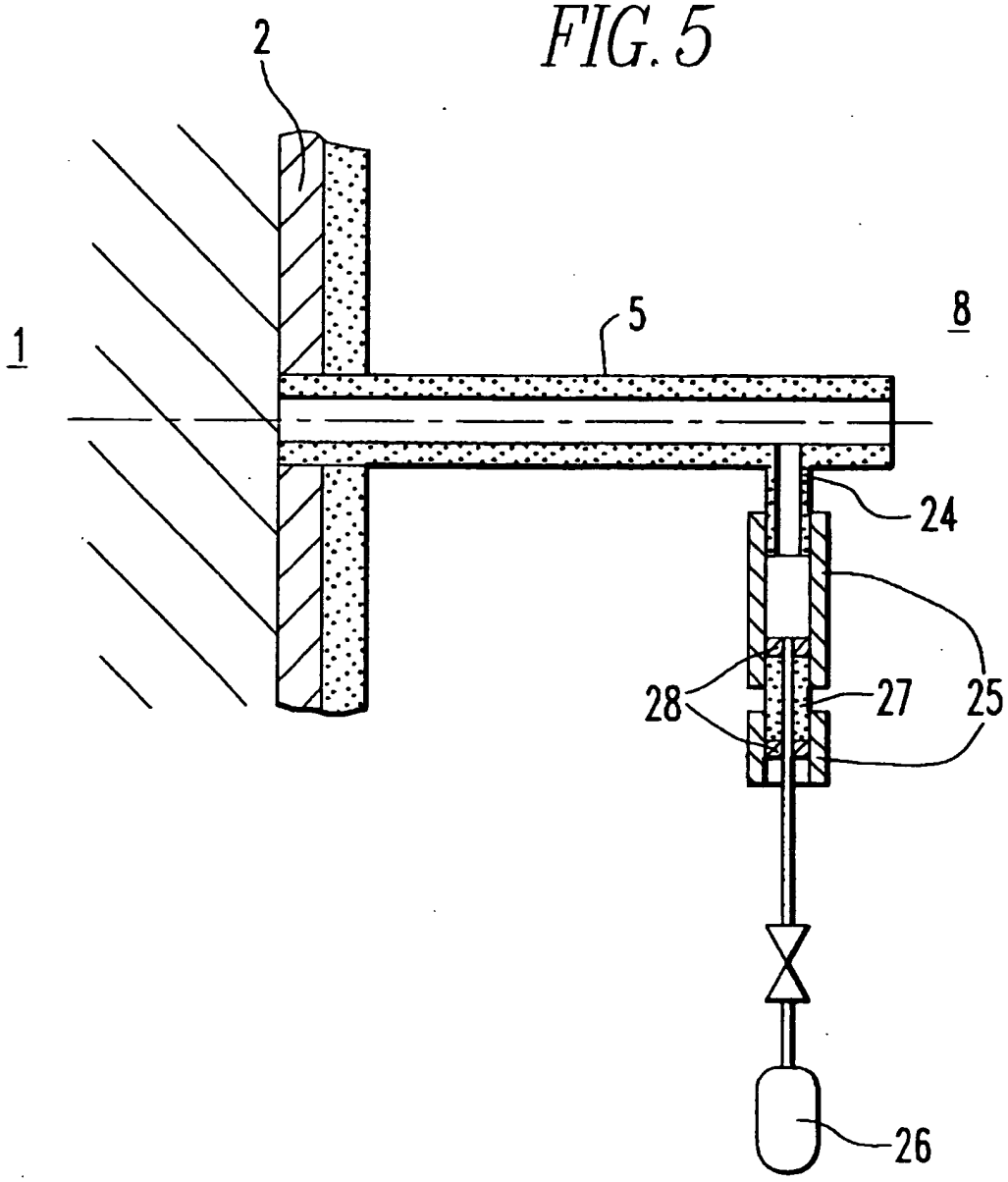


FIG. 6

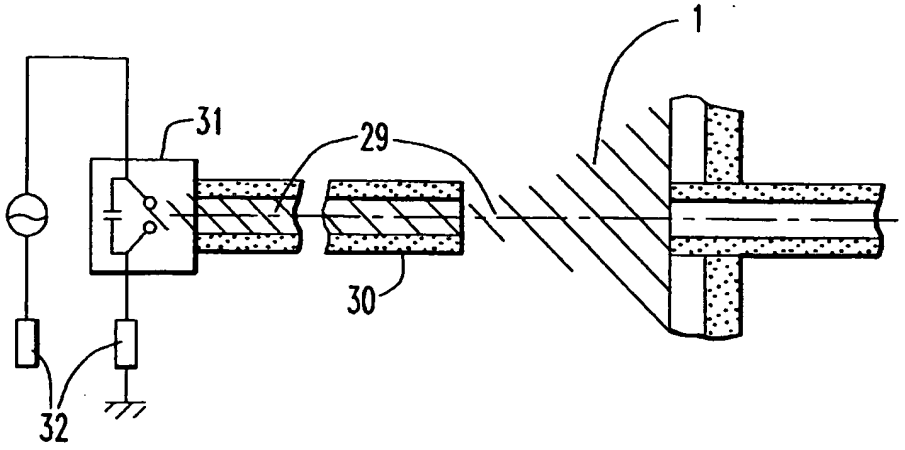
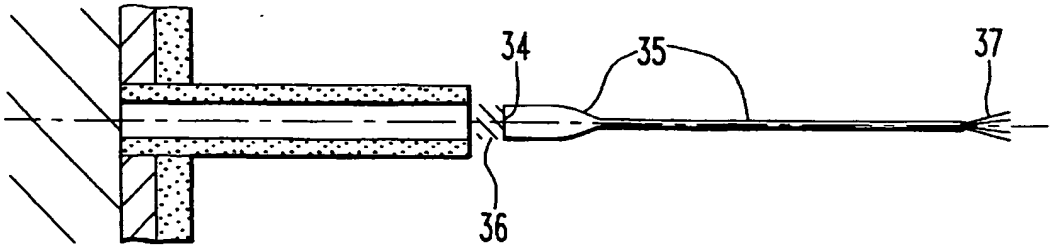


FIG. 7



APPARATUS FOR ACCELERATING ELECTRICALLY CHARGED PARTICLES

This is a continuation-in-part application International application PCT/DE93/00253 filed Mar. 18, 1993, and claiming priority of German application P 42 08 764.3 of Mar. 19, 1972.

BACKGROUND OF THE INVENTION

The invention relates to a particle beam accelerator for generating an electrically charged particle beam.

With such accelerators, particles of a predetermined charge and mass are extracted from a reservoir and supplied to an acceleration chamber formed between two different electrical potentials to finally provide a beam for use in further treatment procedures.

Patent DP 38 34 402 discloses a process in which the magnetically self-focussed electron beam or a pseudo-spark discharge is received at the anode exit of an electrically insulating quartz tube and is transported therein over a certain distance. A slight curvature or the tube has no noticeable effect on the beam transport and accordingly facilitates the search for the most suitable impact angle of the beam onto the target. To a certain degree, the tube protects the pseudo-spark chamber from ablation vapors and permits differential pumping because of the small pump cross-section. The generation or the electron beam with the technically complicated pseudo-spark chamber however is limited with regard to beam strength and divergence.

It is the object of the invention to achieve high particle beam intensities or equivalent thereto a high current, that is, a high current density, and a sharp focussing of the particle beam by economically acceptable means and expenditures.

SUMMARY OF THE INVENTION

In an apparatus for accelerating electrically charged particles from a pulsed plasma reservoir of high particle density in a dielectric tubular chamber which extends from the reservoir and is surrounded by at least two electrodes of which one is disposed at the wall of the reservoir, the dielectric tubular chamber is partially evacuated to a sufficiently low pressure p that the product of the gas pressure p and the inner diameter dot the tubular chamber is low enough to avoid parasitic discharges in the residual gas charge, and a voltage is applied to the electrodes such that the particles are drawn into the dielectric tubular chamber with high flow density and are accelerated therein thereby forming a charged particle beam whereby the residual gas charge in the dielectric tubular chamber is ionized along the inside wall of the tubular chamber and polarized such that the wall of the dielectric tubular chamber becomes repulsive for the charged particle beam and its axis becomes attractive whereby the charged particle beam is electrostatically focussed and exits the dielectric tubular chamber with low losses.

It is essential that the charged particles in the reservoir are inducted, under high current strength and current density, into a dielectric tubular chamber beginning with the electrode which forms part of the reservoir wall and are accelerated there by way of the potential difference between the two electrodes. Upon arrival the particles in a target chamber at the end of the dielectric tubular chamber they have reached their process energy. For the beam formation it is further important that a residual gas charge with the remaining pressure p is ionized in the dielectric tubular chamber by

the particle beam and electrically polarized. The charge cloud at and along the inner tube chamber wall is repulsive with respect to the particle beam. A space charge compensation and an electrostatic focussing the particle beam occurs. This process proceeds well if the product of the residual gas pressure p and the inner diameter d of the tube is so low that the acceleration potential between the electrodes applied from without remains effective essentially for the particle beam acceleration in spite of parasite discharges in the residual gas charge.

In the embodiments described hereafter, additional features are disclosed by which a beam deflection or a change in beam cross-section are achieved. Further, steps for a predetermined beam acceleration are described.

For example a beam deflection is achieved by a locally limited magnetic field in the area of the tubular chamber. By changing the cross-section of the dielectric tubular chamber the cross-section of the particle beam is changed.

For the adjustment of the process energy of the particle beam or its beam strength it may be suitable to reduce the length of the acceleration distance by means of a resistively or inductively coupled auxiliary electrode arranged between the two electrodes. In addition the acceleration distance for the particle beam is divided in a well defined manner by a potential control via resistively coupled auxiliary electrodes arranged between the two main electrodes.

For the performance of the process the particle accelerator as described herein is well suited. In order to be capable to withdraw the charged particles from the reservoir with a strong flow, one of the electrodes forms part of the reservoir wall. The tubular dielectric space begins at such electrode or others if a plurality would be suitable. The opposite electrode is arranged outside the reservoir. The dielectric tubular chamber extends toward the opposite electrode.

It was found experimentally that the geometry of the arrangement is optimal when the length of the tubular chamber is at least three times its inner diameter. In order to maintain the axial electrical insulation even with contamination, the tubular chamber is formed suitably partially or fully by a system of aligned dielectric tube segments. The segments together define radially shaped slots which prevent surface currents.

Advantageously the slot arrangement is provided in such a way that radiation or particles emanating radially from the tube axis will not reach the radial slot end or only by way of a long detour.

For the improvement of the particle beam formation, an electrically sufficiently insulated gas supply is arranged at the end of the tube adjacent the opposite electrode by which gas can be supplied to the tubular chamber in opposite directions.

A noticeable quality improvement of the particle beam can be attributed at one hand essentially to the replacement of the pile of electrodes and insulators of the pseudo-spark length by a tubular chamber delimited by a dielectric material which, in the example described below, is a quartz tube or an assembly of aligned quartz tube sections. On the other hand, the high beam quality is, to a large extent, the result of the particular formation of a charged particle flow with quartz tube arrangement.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1*a* is a schematic representation of the acceleration and transport path for the particle beam;

FIG. 1*a* shows a cross-section through the dielectric tube with positive space charge along the axis and negative space charge collection along the tube wall as when the particle beam is formed by electrons;

FIG. 2 shows a curved acceleration and transport path in a receiver with additional magnetic beam focussing;

FIG. 3*a* shows a division of the dielectric tube into acceleration and transport paths by mean of an auxiliary electrode;

FIG. 3*b* shows potential control by means of auxiliary electrodes arranged between the end electrodes;

FIG. 4*a* shows a basic radial tube chamber expansion between the tube segments;

FIG. 4*b* shows a constructively simple tube chamber expansion;

FIG. 4*c* shows a constructively involved tube chamber expansion;

FIG. 5 shows a tube space with electrically uncoupled pumping device;

FIG. 6 shows an electrically high-charge particle reservoir, a simple schematic example for the particle generation and the withdrawal into the tubular chamber; and

FIG. 7 shows a pulsed light source.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In an involved testing procedure it was found that the electron beam which leaves the quartz tube consists of two components, specifically one component from the gas discharge in the pseudo-spark chamber and a component derived from the authentic beam formation in the quartz tube.

First, the electron beam from the pseudo-spark chamber is coupled into the dielectric tube reliably only if the end of the dielectric tube is disposed on an intermediate electrode and it does this better the more cathodically the dielectric tube is charged, that is, the deeper it is inserted into the pseudo-spark chamber.

Measurements with a voltage sensing head show that, then, the electrons from the pseudo-spark chamber charge the intermediate electrode on which the dielectric tube is disposed strongly negatively (up to cathode potential) within 100 ns whereupon the cathode end of the dielectric tube draws in electrons from the plasma in the canal of the pseudo-spark chamber and forms an electron beam which, with regard to travel range (after leaving the dielectric tube), parallelism and efficiency, is superior to the pseudo-spark chamber electron beam. The plasma in the canal of the pseudo-spark chamber serves as an electron source and reservoir.

In this manner, it is possible in accordance with the invention to generate in an apparatus (FIG. 1*a*) magnetically self-focussing electron beams **7** which apparatus, for example, consists of a pulsed, high density plasma reservoir **1**, of a rapidly variable hollow cathode and of a dielectric tube **5** extending into the cathode and having one end with an opening **4** in communication with the reservoir **1**. The other end of the dielectric tube **5** extends—insulated from the cathode electrode **2**—freely into a receiver **8** (see FIG. **2**).

From this end a sharply focussed electron beam **7** with a half-width time of 100 ns is formed which, even after 6 cm of free travel, still shows ablation effects as indicated in FIG. **2** by the material cloud **33**.

In the arrangement described, the anode **3** plays a subservient role. The anode **3** may even be eliminated.

The role of the anode **3** is then taken over by the metallic receiver **8**. Both collect the negative excess charge and, from it, form the return current to the capacitors.

For the generation of particle beams **7** of high flow density such as $10^4 A/cm^2$ for electrons, external electrostatic or magnetic focussing is insufficient. For the reduction the space charge, the dielectric tube chamber must include a residual gas charge with a pressure p. The particle beam **7** ionizes and polarizes the remaining gas so that the wall of the dielectric tubular chamber **5** is repulsive for the particle beam **7** and the axis is charged to be attractive (see schematic representation in FIG. 1*b*). Because of the distribution of the negative space charge **38** over the interior wall of the tube **5**, the space charge repulsion along the axis **12** is reduced or the electron beam **7**. At the same time, the negative charge **38** at the wall is drawn out of the tube **5** by the outer electric field such that the charge carriers, which have been formed by the gas, provide for a positive excess charge **39**. This positive excess charge **39** reduces the negative space charge coming with the beam **7**.

The profile of the electron beam is similar to a hollow cylinder. This suggests a remaining space charge repulsion during the acceleration process. Upon leaving the tubular chamber **5** the beam **7** remains stable and expands only slightly along a travel distance of 15 cm; but the residual pressure in the receiver **8** must not exceed 0.2 Pa (oxygen). The profile of the beam **7** points to the capacity of the tubular chamber **5** to also retain and accelerate those electrons which would split from the beam in an open acceleration arrangement. This explains the high efficiency of the particle acceleration in the tubular chamber **5**. But to avoid electron losses, the dielectric tube **5**, that is, its first section, must have a length of at least three times its inner diameter.

In the given example for the generation of an electron beam, the voltage collapse at the tube **5** occurs at about 4 Pa with an applied voltage of 20 kV and a diameter d of the dielectric tube of 3 mm. The preferred operating pressure range for the given example is between 0.1 Pa and 1.5 Pa. As gas charge, oxygen was utilized, but any other gas may be used for residual gas charge.

The diagnosis of the energy distribution of the electrons by means of X-ray heterochromatic radiation and magnetic field spectroscopy shows that, in the preferred pressure range mentioned above, the energy distribution of the electrons remains constant as a result of the collective effects thereof. With an externally applied voltage of 20 kV, an average electron energy of 11 to 12 keV is measured over a period 70 nsec independently of fluctuations in the total flow in the tube which reaches up to 6 kA.

It is found that the extracted electron flow increases if an auxiliary electrode **9** is integrated into the dielectric tube **5** which is connected to the anode **3** (FIG. 3*a*) by way of an ohmic or inductive resistor **10**. The resistor **10** is so dimensioned that, beginning with a small current (10 mA-10 A) the anode potential drifts away from the auxiliary electrode **9** and the potential is applied to the dielectric tube **5** as a whole. This measure is recommended generally, but particularly then, when the dielectric tube **5** is very long (for example, 100 cm) and/or curved and/or if, for a reduction or an increase in the current density, the cross-section along the dielectric tube is changing. If the dielectric tube is curved as shown in FIG. **2**, also spaced magnets **15** are provided to apply locally limited magnetic fields to the beam for bending the beam.

The length from the reservoir 1 to the auxiliary electrode 9 in FIG. 3*a* is called canal accelerator 11 and the formation of the particle beam 7 is called canal discharge. The section from the auxiliary electrode 9 to the anodic end of the dielectric tube 5 is designated beam guide 17.

The electric insulation capability of the inner wall 23 of the accelerator tube 5 is impaired by contamination; this will result in a misfunction in the operation of the canal discharge. Also, the occurrence of a secondary discharge in the adsorbates of the inner wall 23 of the dielectric tube 5 is unavoidable when the particle flow from the reservoir 1 increases. The discharge at the inner wall of the dielectric tube 5 leads to a shielding of the outer field whereby the focussing of the particle beam 7 from the reservoir 1 onto the tube axis is inhibited. To suppress full-length wall currents, FIGS. 4*a*, 4*b* and 4*c* show three examplary solutions for a segmented arrangement 16 of the tube 5, each time in connection with a dielectric body 18, 19, 20 which includes an inner radial gap or any topological slot formation, which results in a disruption of possible damaging inner surface currents along the wall 23, from one to another dielectric tube segment. The slots may also include a recess 22 or similar which prevents the passing of vapors into the remote slot areas. In this manner isolation of the segments from one another is insured which results in reliable functioning of the canal discharge.

It is also possible to utilize, in place of a rapidly variable hollow cathode, a pulsed surface discharge—or laser plasma as reservoir 1 for electrons as shown in FIG. 1*a*. For the transportation of the high-current beam in the anode chamber it is however necessary to maintain a minimum pressure of about 0.2 Pa.

If the reservoir 1 is at a high potential a trigger plasma 29 can be conducted through a dielectric tube 30 of about the same diameter and the same length as the canal accelerator tube 11 into the reservoir 1 and operation can then be initiated. The other end of the dielectric tube is grounded with the trigger source 31 by way of a resistor 32 in such a way that possible side discharges to the trigger source 31 are not destructive (see FIG. 6).

Pressure differences between the reservoir 1 and the target chamber or receiver 8, in which the opposite electrode 3 is disposed, can be easily achieved by differential pumping since the pump resistance of the dielectric tube 5 increases with the inner diameter in the 4th exponent and linearly with its length. A reliable protection of the whole dielectric tube system from contamination is insured if, at the end of the dielectric tube 5 toward the opposite electrode 3, a gas supply 24 is connected to the tube 5 so that the gas can enter in the direction toward the reservoir 1 as well as toward the receiver 8 in which the opposite electrode 3 is disposed (FIG. 5). To avoid parasitic gas discharges between the dielectric tube 5 and the gas source 26 it is necessary to provide in the gas admission hose 25 between the end of the tube and the gas source 26 a further dielectric tube portion 27 which has an inner diameter of at most ½ d and is metal coated at both end faces or has electrodes 28 at its end faces wherein the electrode 28 facing the gas source 26 is grounded and the other is free-floating.

For the acceleration of ions the potential of the reservoir 1 is at anode potential. Because of the shielding effect of the electrons and the small movability of the ions the density of the plasma in the reservoir 1 at the entrance to the dielectric tube 5 needs to be high. For an effective withdrawal of the ions out of the plasma into the dielectric tube 5, the acceleration section (up to the first auxiliary electrode 13*a*, see FIG. 3*b*) needs to be short and, because of the Child-Langmuir law, the potential must be selected to be high. The auxiliary electrode then begins to carry current. The ohmic or inductive resistors 6 via which the auxiliary electrodes 13*a*, 13*b*, 13*c* and the cathode are interconnected permits the first auxiliary electrode 13*a* to drift down to anode potential. Then a subsequent second auxiliary electrode 13*b* takes over the build-up of an electric field and then also this electrode is deactivated by a current load, a subsequent electrode 13*c* takes over, etc. (see FIG. 3*b*). In order to keep the operating cross-sections for the recharging with ions log, the residual pressure must be as low as possible. In an examplary embodiment it was at about 0.1 Pa.

This way of accelerating ions has two advantages: Firstly, the auxiliary electrodes 13 operate like a linear accelerator; secondly, the ion beam leaves the dielectric tube 5 in good parallelism.

The canal discharge is first of all a simple and cost efficient source for high-current oriented electron and ion beams by which process energy can be deposited in static or differentially pumped gases, gas mixtures and mixtures of gas and aerosoles. For example, by differential pumping in the dielectric tube 5, a gas target can be created in which the electron beam is slowed down in the gas while generating deceleration and characteristic radiation. Aerosoles of unknown composition can be continuously conducted through the dielectric tube wherein they are totally ionized by the electron beam and can be identified on the basis of their characteristic radiation.

By means of the particle beams, material can be irradiated, removed and worked (see FIG. 2). The removal process in the case of electrons is ablation; in the case of ions, it is atomization including hot processes.

The sputtered, ablated and atomized materials 33 mainly move away from the target 14 in a direction normal to the target 14 and consist, about in the order of the power density of the particle beam, of ions, atoms, molecules, clusters and aerosoles of any size which are partly still excited and carry excess charges.

The target material which has been sputtered, ablated and vaporized by the particle beam can be utilized for the manufacture of layers of substrates by the Tayloring process (each atomic layer is different), as atomic mixture (between otherwise incompatible materials) and as compound material on high-strength fibers or similar.

Layers of substrates can also be manufactured with atomic material which is released from a gaseous chemical compound by exposure to the particle and/or electromagnetic radiation.

The high-current electron/ion beams from the canal discharge form a particle source of high definition and high current flow and, after passing a differentially pumped passage, can be introduced into intermediate and high energy accelerators.

The plasma formed upon impingement of the particle beams onto a target is a powerful pulsed source of electromagnetic radiation (light, UV, VUV, soft X-ray radiation).

A very intense pulsed light source 37 is obtained by bombarding the front face 34 of a light conductor 35 with the particle beam (see FIG. 7). Hereby, a very hot plasma 36 is generated from the light conductor material providing for light radiation which, because of its spectral composition and high density at the point of generation, is coupled into the light conductor with high efficiency.

Concurrently with the generation of the electron beam, a plasma is formed in the dielectric tube and microwaves are

generated by the interaction of the electron beam with the plasma which pass through the dielectric tube and exit therefrom in an unattenuated and undisturbed condition.

At the cathodic entrance of the dielectric tube a zone of very hot plasma is formed. If the canal discharge is used as a process preceding a subsequent z-pinch, this area can be magnetically compressed over an extended period and can be heated by ohmic procedures. In this manner, it is possible to maintain the plasma for more than a microsecond at a temperature of Te=200 eV with a primary energy of only 15 joules. By predetermined contamination with atoms of higher atomic number a simple plasma source of light, UV, VUV and soft X-ray radiation up to an energy of 2 keV becomes available. Because of the low linear density of the plasma formed from the residual gas, the line widening of the radiation is also very small. The efficiency of the emitted radiation of between 10 eV and 2 keV is about 10%, that of the radiation between 700 eV and 2 keV is less than one part per mille (1/1000).

The electron beam of the canal discharge is characterized by a high current in the lower kA-range with a comparably low acceleration voltage (5–10 kV) and is suitable for the generation of pulsed soft heterochromatic radiation upon impingement of the well-focussed electron beam onto a target. With this heterochromatic radiation, biological structures in the micrometer range can be depicted by shadow formation.

Since, at the canal accelerator 11, voltage differences of up to 100 kV can be maintained, the canal discharge is suitable for use as an uninhibiting and switchable switch for high voltages. For lower voltages the canal discharge may also be used as an impulse generator with repetition frequencies up to 100 kHz.

What is claimed is:

1. A particle accelerator for accelerating electrically charged particles, comprising: a pulsed plasma reservoir of high particle density, a dielectric tubular chamber having an inner diameter d and extending from said reservoir, at least two electrodes disposed around said tubular chamber in spaced relationship from one another, one electrode being arranged along on inside wall of said reservoir, means for evacuating said dielectric tubular chamber to maintain only a residual gas charge with a sufficiently low pressure p such that the product of the gas pressure p and the inner diameter d of the dielectric tube (pxd) is low enough to avoid parasitic discharges in said residual gas charge, means for applying a voltage to said electrodes for drawing said charged particles from said reservoir into said dielectric tubular chamber and for accelerating them therein so as to form a charged particle beam in said dielectric tubular chamber by which the residual gas charge in said dielectric tubular chamber is ionized along the inside wall thereof and polarized providing for wall repulsive and axis attractive forces capable of electrostatically focusing said charged particle beam exiting said dielectric tubular chamber.

2. A particle accelerator according to claim 1, wherein said dielectric tubular chamber has a minimum length of three times its inner diameter.

3. A particle accelerator according to claim 1, wherein, for maintaining the axial electrical insulation during contamination, said dielectric tubular chamber between said two electrodes is formed by a system of dielectric tube segments arranged in coaxial alignment and interconnected by dielectric bodies with coaxially aligned internal passages having inner radial slots by which the flow of inner surface currents between said tube segments is prevented.

4. A particle accelerator according to claim 3, wherein said slots of the dielectric bodies include further a recess such that a subsequent rear space following the recess is protected from contamination and surface conductivity.

5. A particle accelerator according to claim 1, wherein near the end of said dielectric tubular chamber toward the other electrode, a gas supply with a gas supply hose is provided through which gas can be supplied so as to flow toward said reservoir and toward a receiver, in which the other electrode is disposed.

6. A particle accelerator according to claim 5, wherein a dielectric tube is disposed in said gas supply hose between said tubular chamber and a gas source, and, for preventing a parasitic gas discharge to the gas source, the dielectric tube has an inner diameter of at most ½ the diameter of said dielectric tubular chamber and opposite end faces provided with two electrodes of which one electrode which is closer to said gas source is grounded and the other is free-floating.

7. A particle accelerator according to claim 1, wherein said reservoir comprises a pulsed high density plasma.

8. A particle accelerator according to claim 1, wherein said reservoir is maintained at an electrically high potential, and a dielectric tube which has about the same inner diameter and the same length as said dielectric tubular chamber is connected at one end to said reservoir and at the other end to a trigger charge source for conducting a trigger charge flow of low energy to the reservoir through said dielectric tube.

9. A particle accelerator according to claim 8, wherein said dielectric tube, through which the trigger charge flow of low energy is supplied to the reservoir, is grounded at its other end by way of a resistor such that side discharges to the trigger source cannot cause any damage.

10. A particle accelerator according to claim 1, wherein means are provided for applying locally limited magnetic fields to the particle beam in said dielectric tubular chamber at predetermined locations to achieve a predetermined deflection of the beam.

11. A particle accelerator according to claim 1, wherein the flow density of the particle beam exiting from said dielectric tubular chamber is controlled by varying the cross-section of said dielectric tubular chamber.

12. A particle accelerator according to claim 11, wherein a ring shaped auxiliary electrode is disposed in a dielectric wall of said tubular chamber.

* * * * *

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[45] Date of Patent: Aug. 16, 1994

[54] METHOD FOR MICROBEAM RADIATION THERAPY

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[73] Assignee: The United States of America as represented by the United States Department of Energy, Washington, D.C.

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[51] Int. Cl.[5] A61N 5/10

[52] U.S. Cl. 378/65; 378/64; 378/149

[58] Field of Search 378/65, 64, 68, 147, 378/149

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[57] ABSTRACT

A method of performing radiation therapy on a patient, involving exposing a target, usually a tumor, to a therapeutic dose of high energy electromagnetic radiation, preferably X-ray radiation, in the form of at least two non-overlapping microbeams of radiation, each microbeam having a width of less than about 1 millimeter. Target tissue exposed to the microbeams receives a radiation dose during the exposure that exceeds the maximum dose that such tissue can survive. Non-target tissue between the microbeams receives a dose of radiation below the threshold amount of radiation that can be survived by the tissue, and thereby permits the non-target tissue to regenerate. The microbeams may be directed at the target from one direction, or from more than one direction in which case the microbeams overlap within the target tissue enhancing the lethal effect of the irradiation while sparing the surrounding healthy tissue.

44 Claims, No Drawings

METHOD FOR MICROBEAM RADIATION THERAPY

This invention was made with U.S. Government support under Contract Number DE AC02-76CH00016 between the U.S. Department of Energy and Associated Universities, Inc. The U.S. Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to methods for performing radiation therapy for cancer treatment. More particularly, the invention relates to methods of using arrays of small radiation beams to irradiate tumors.

2. Background of the Related Art

Cancer continues to be one of the foremost health problems. Conventional treatments such as surgery and chemotherapy have been extremely successful in certain cases; in other instances, much less so. Radiation therapy has also exhibited favorable results in many cases, while failing to be completely satisfactory and effective in all instances. A much less familiar alternative form of radiation therapy, known as microbeam radiation therapy (MRT), is being investigated to treat certain tumors for which the conventional methods have been ineffective.

MRT differs from conventional radiation therapy by employing beams of radiation that are one order of magnitude smaller in diameter than the smallest radiation beams currently in clinical use. The diameter of the microbeams is dependent upon the capacity of tissue surrounding a beam path to support the recovery of the tissue injured by the beam. It has been found that certain types of cells, notably endothelial cells lining blood vessels, have the capacity to migrate over microscopic distances, infiltrating tissue damaged by radiation and reducing tissue necrosis in the beam path. In MRT, sufficient unirradiated or minimally irradiated microscopic zones remain in the normal tissue, through which the microbeams pass, to allow efficient repair of irradiation-damaged tissue. As a result, MRT is fundamentally different from other forms of radiation therapy.

In conventional forms of radiation therapy, including the radiosurgical techniques employing multiple convergent beams of gamma radiation described by Larsson "Potentialities of Synchrotron Radiation in Experimental and Clinical Radiation Surgery," *Acta Radiol Ther. Ph. Biol. Suppl.*, 365, 58–64 (1983), each beam is at least several millimeters in diameter, so that the biological advantage of rapid repair by migrating or proliferating endothelial cells is minimal or nonexistent. As described in greater detail below, our observations of the regeneration of blood vessels following MRT indicate that endothelial cells cannot efficiently regenerate damaged blood vessels over distances on the order of thousands of micrometers (μm). Thus, in view of this knowledge concerning radiation pathology of normal blood vessels, the skilled artisan would optimally select microbeams as small as 50 μm to 200 μm in diameter.

The division of a radiation beam into microbeams, and the use of a patient exposure plan that provides non-overlapping beams in the tissue surrounding the target tumor. This allows the non-target tissue to recover from the radiation injury by migration of regenerating endothelial cells of the small blood vessels to the areas in which the endothelial cells have been injured beyond recovery. Therefore, the probability of radiation-induced coagulative necrosis in normal, non-targeted tissue is lowered, which should improve the effectiveness of clinical radiation therapy for deep-seated tumors. The use of microbeams should be of special benefit for deep pulmonary, bronchial, and esophageal tumors, for example, where the effectiveness of orthodox radiation therapy is limited by the risk of radiation pneumonitis.

Effects on the mouse brain of 22 MeV deuterons delivered in a beam having either a circular cross-section (herein designated a "cylindrical" beam) 25 μm in diameter or an elongated rectangular cross-section (herein designated a "planar" beam) 25 μm in width were investigated 3 decades ago. Representative investigations are described by Ordy et al., "Long-Term Pathologic and Behavioral Changes in Mice After Focal Deuteron Irradiation of the Brain", *Radiation Research* 20, 30–42 (1963). The Ordy et al. publication describes the effects of exposure to high energy deuteron microbeams having a 9 mm ×0.025 mm planar configuration. These beams of heavy charged particles were used in experiments to model the neurological effects of extraterrestrial heavy ions on humans. Ordy et al. do not discuss the treatment of tumors by X-ray microbeam irradiation.

Damage to the cerebrum and cerebellum caused by the deuteron microbeam, was not evident unless a very high radiation dose was given. A macroscopic (1 mm diameter) 22 MeV deuteron beam that delivered about 150–300 Gray (Gy) to the mouse cerebrum caused tissue necrosis in its path. On the other hand, energies of at least 3000 Gy to the cerebral cortex or 720 Gy to the cerebellar cortex were required to leave any persistent brain damage in the path of a 22 MeV, 25- to 40-μm-wide cylindrical or planar deuteron microbeam, as observed by light microscopy up to 9 months after irradiation. Furthermore, damage was limited to cellular necrosis. Tissue necrosis in the microbeam-damaged zone of the mouse brain was apparently averted by regeneration of blood vessels, even after an absorbed dose of 10,000 Gy or more in the path of the microbeam. Any vascular or parenchymal cell in the microbeam that had been so intensely irradiated was probably destroyed. Cellular necrosis caused by the deuteron microbeam depended mainly on the absorbed dose rather than on the absorbed dose rate, which was varied from 2 to 9,000 Gy s^{-1}.

These unprecedented dose-effect relationships in the brain were attributed to the narrowness of the beams and to the regeneration of blood vessels in tissues within the path of the microbeam from the microscopically contiguous, minimally irradiated vasculature adjacent to that path. Presumably, minimally irradiated blood vessels contained reservoirs of endothelium from which regenerating endothelial cells grew into the nearby, maximally irradiated blood vessel segments as the endothelial cells of the latter segments died and disintegrated.

A microbeam tissue-sparing effect was also observed for X-ray microbeams by Straile and Chase, in "The Use of Elongate Microbeams of X-Rays for Simulating the Effects of Cosmic Rays on Tissues: A Study of Wound Healing and Hair Follicle Regeneration", *Radiation Research*, 18, 65–75 (1963). This publication describes the irradiation of mouse skin using a 200 kVp, 0.5 mm Cu+1.0 mm Al-filtered X-ray source. Absorbed doses of about 60 Gy produced a variety of skin

lesions when delivered in a seamless (i.e., not spatially interrupted) 5 mm diameter beam. However, much less severe damage occurred when similar doses were delivered to the skin via a 150 μm wide microbeam. These investigators were primarily concerned with modelling the effects of cosmic rays, and did not describe or suggest the use of microbeams for any therapeutic purposes.

A publication by L. Leksell, "The Sterotaxic Method and Radiosurgery of the Brain," *Acta Chirugica Scandinavia*, 102, 316–319 (1951), describes a stereotaxic instrument suitable for cross-firing radiation treatment of brain tumors. The Leksell publication does not describe the use of microbeams or of multiple simultaneous beams. A related publication by B. Larsson entitled "Potentialities of Synchrotron Radiation in Experimental and Clinical Radiation Surgery," *Acta Radiol. Ther. Ph. Bios. Suppl.*, 365, 58–64 (1983), which further describes the stereotaxic method of Leksell. In addition, Larsson describes a hemispherical helmet-like apparatus for gamma radiation of intracranial targets by multiple converging channels. Larsson does not, however, discuss microbeams or any method of producing microbeams.

U.S. Pat. No. 2,638,554 to Bartow et al. describes various collimators for X-rays which produce a conically converging array of very small beams. One of the collimators described by Bartow et al. is a truncated cone of X-ray-impermeable material cast around a removable array of wires. Once the wires are removed, an array of apertures remains in the collimator which, when inserted into a beam of X-rays, will produce a convergent array of very small beams. The apertures are described as being in the range of 0.25 inches (6.4 mm) to 0.001 inches (25.6 μm). Another lens described by Bartow et al. is an arcuate lens assembled from planar segments into which grooves have been cut so that when assembled each of the isofocused grooves defines an X-ray transmissive aperture. Neither of the Bartow et al. collimators produces planar beams.

The Bartow et al. patent describes avoidance of excessive concentration of X-rays at any particular spot on the subject skin or tissues by virtue of the discretely spaced small beams. The Bartow et al. patent also describes the rotational or translational movement of the emitting device to produce a cross-firing effect. The Bartow et al. patent does not, however, present any description of a tissue sparing effect at a microscopic level that might be attributable to the specific use of microbeams, positioned to produce just such an effect. Neither do Bartow et al. describe the use of parallel microbeams or the efficacy of the treatment of tumors using parallel microbeams without any converging or cross-firing effect.

U.S. Pat. No. 4,827,491 to Barish also describes accelerator beam collimators having at least one radiation transmission channel. The beams produced by the Barish collimator are generally convergent toward a predetermined target, and range in diameter from about 3 mm to about 4 mm. The Barish collimators are described as useful for the radiation treatment of intra-cranial tumors, but may be applied to treatment of other portions of the body. The Barish patent does not describe microbeams or their utility.

U.S. Pat. No. 2,624,013 to Marks describes a radiation barrier or collimator producing a plurality of relatively large, parallel, rectangular beams. The beams range in size from 0.25 inch to 1 inch on each side. The Marks patent describes the protection of skin by limiting the irradiation of the skin to areas between the beams, thereby helping to retain the skin's integrity. The internal efficacy of the radiation beams produced by the Marks invention is described as relying on recoil electrons to destroy internal tumors. The Marks patent does not describe converging beams or the use of microbeams.

U.S. Pat. No. 4,726,046 to Nunan describes a method and apparatus for generating a relatively small (0.5 mm ×0.5 mm) radiation beam. The Nunan method employs a plan for producing an array of radiation exposures by sequentially scanning over a prescribed area and intermittently delivering radiation beams, but does not describe microbeams.

U.S. Pat. No. 2,139,966 to Loebell describes an X-ray apparatus designed to emit a plurality of convergent X-rays for the treatment of internal disorders. The Loebell apparatus employs several independently movable, X-ray emitting cathode/anode pairs, preferably arranged radially arranged to produce a converging array of beams. The Loebell apparatus is described as capable of eliminating the burning of skin area by the use of converging beams. The Loebell patent does not describe the use of microbeams.

U.S. Pat. No. 4,592,083 to O'Brien describes a rotating shutter for radiation beams. The high speed actuator for controlling the shutter eliminates transition time during which the X-ray dose is wasted. Also describing a beam shutter is U.S. Pat. No. 3,963,935 to Donnadille. This shutter is described as useful for limiting the entry of radiation beams from particle accelerators into irradiation rooms. Neither of these patents describes the use of either single or arrayed microbeams for radiation treatment of tumors.

U.S. Pat. No. 5,125,926 to Rudko et al. describes a system for synchronizing the pulsation of a surgical laser with the heartbeat of a patient undergoing laser heart surgery. The Rudko et al. patent does not describe the synchronization of radiation beams for cancer therapy. Rudko et al. also do not describe the use of the synchronization method with tissues other than heart tissue. Furthermore, Rudko et al. do not disclose the synchronization of radiation impulses with other physiomechanical rhythms.

Although other methods and processes are known for radiation therapy, none provides a method for performing radiation therapy while avoiding significant radiation-induced damage to tissues surrounding the target.

Accordingly, it is a purpose of the present invention to provide a method for treating cancerous tumors by using extremely small radiation microbeams increasing the precision and accuracy of radiation therapy.

It is also a purpose of the present invention to provide a method of using extremely small microbeams of radiation to unexpectedly produce effective radiation therapy.

It is a further purpose of the present invention to provide an improved method of radiation therapy unexpectedly capable of avoiding significant radiation-induced damage to non-target tissues.

Other purposes and advantages of the present invention will be more fully apparent from the ensuing disclosure and appended claims.

SUMMARY OF THE INVENTION

These and other purposes are achieved by the present invention which solves the disadvantages inherent in

the prior art by providing a method for performing microbeam radiation therapy (MRT), a specialized technique related to stereotactic radiosurgery.

In contrast to general stereotactic radiosurgery, MRT radiation microbeams having extremely small widths (<500 μm), to irradiate a target, generally a tumor. In MRT, parallel or nearly parallel X-rays are delivered to the target as a spatially fractionated (i.e., microscopically segmented) radiation field, containing a number of microbeams, each microbeam typically being between about 20 μm and about 200 μm wide. Interstitial zones of relatively unirradiated tissue remain between the areas of tissue through which the microbeams pass. These unirradiated zones are typically about 50 μm to about 500 μm wide, depending on the width of microbeams and on other irradiation parameters such as beam energy, dose, and geometry. The beam energies can range from about 30 to several hundred keV.

The method of the present invention employs radiation fields having any of a variety of geometrical configurations. A preferred geometrical option is to employ a linear array of substantially parallel planar microbeams (i.e. microbeams having greatly elongated rectangular cross-sections). While the narrow side of each beam cross-section typically measures between about 20 μm and about 150 μm, the wide side may be as large as in the range of several millimeters to several centimeters. The bundle of microbeams can therefore include substantially parallel, non-overlapping, planar beams with center-to-center spacing of from about 50 μm to about 500 μm; or converging planar beams intersecting at or near the isocenter of the target.

Another geometrical option is a 2-dimensional array of substantially parallel or converging, radially symmetrical, microbeams (e.g., with circular cross-section), having diameters of from about 20 μm to about 200 μm and center-to-center spacing of from about 50 μm to about 500 μm.

Irrespective of whether planar or cylindrical beams are employed, the patient exposure can be performed either unidirectionally (i.e., by exposure of the target using an array of microbeams having one general direction), or from multiple directions allowing the beams to intersect at the isocenter (i.e., the "cross firing" option). These options are also available independently of whether the microbeams in any one array are parallel of convergent.

A major benefit of MRT is that the microbeams are so narrow that the vasculature of the tissue through which the microbeams pass can repair itself by the infiltration of endothelial cells from surrounding unirradiated tissue. Present knowledge indicates that such infiltration can take place only over distances on the order of less than 500 μm depending on the tissue being irradiated. The dimensions of the microbeams and the configuration of the microbeam array are therefore determinable with reference to the susceptibility of the target tissue and the surrounding tissue to irradiation and the capacities of the various involved tissues to regenerate.

Another aspect of the present invention is that the microbeam radiation therapy may be conducted in a pulsed mode. The pulses may be synchronized with either the cardiac or the respiratory cycle or both. Each pulse is limited to a small time interval during the appropriate cycle to avoid the smearing of the extraordinarily precise microbeam effect by movement of the tissue generated by cardiogenic and respiratory pulsation.

For a better understanding of the present invention reference is made to the following description, the scope of which is pointed out in the claims.

DETAILED DESCRIPTION OF THE INVENTION

In microbeam radiation therapy, radiation is delivered to a clinical target, usually a cancerous tumor, as a spatially fractionated field containing a number of microbeams. The field or array of microbeams is generally described with reference to the geometrical arrangement of the microbeams as they pass through an imaginary plane perpendicular to the path of the microbeams. The microbeams do not overlap unless they are at the target volume. Accordingly, the field will comprise areas of high radiation intensity corresponding to the beam cross-sections, as well as areas through which the beams do not pass having relatively low radiation intensity at the interbeam spaces.

MRT in accordance with the present invention may be performed unidirectionally or from more than one direction. Our recent studies have unexpectedly indicated that multiple, parallel planar microbeams, directed at tumors in rat brains from only one direction can result in significant tumor growth control (see Examples 1 and 2). Alternatively, in accordance with previous studies of cross-firing of radiation, it is believed that irradiation of tumors by multiple, angularly displaced, isocentric bundles of microbeams can be efficacious in controlling tumor growth rate (see Example 3).

In observing the known tissue sparing of 22 MeV deuteron microbeams in the mouse brain and exemplary Monte Carlo computations, we inferred that endothelial cells in the brain which are lethally irradiated by any microbeam in an array of adequately spaced microbeams outside an isocentric target are replaced by endothelial cells regenerated from microscopically contiguous, minimally irradiated endothelium in intermicrobeam segments of brain vasculature. Endothelial regeneration mitigates necrosis of the nontargeted parenchymal tissue. However, it is believed neoplastic and/or nonneoplastic targeted tissues at the isocenter are so severely depleted of potentially mitotic endothelial and parenchymal cells by multiple overlapping microbeams that necrosis ensues.

Types of radiation useful for the present invention include, high energy electromagnetic radiation, such as X-ray or gamma radiation. Most preferably the radiation is X-ray radiation. In any generated photon beam, the photons are produced having a characteristic spectrum of energies. The photon energy of the beams useful in the present invention is in the range of from about 30 key to about 300 keV. Most preferably, the energy of the beam is in the range of from about 50 keV to about 150 keV.

Recently, a synchrotron-generated X-ray beam has become available, having practically no divergence and a very high fluence rate. These synchrotron generated X-rays have the potential for projecting sharply defined beam edges deep in the body. This source appears to be potentially useful for generating X-ray microbeams for radiobiology, radiotherapy, and radiosurgery. A high fluence rate is required to implement microbeam radiation therapy (MRT) or microbeam radiosurgery since exposure times must be short enough (e.g., less than about 1 second) to avoid the blurring of margins of the irradiated zones of tissue due to body or organ movements. Sharply defined microbeam margins are made

possible not only by the high fluence rate and the minimal divergence of the synchrotron beam, but also by the microscopically short ranges in tissue of secondary electrons (Compton scattering) generated by 50–150 key synchrotron X-rays. Absorbed doses to nontargeted tissues situated between microbeams can be kept below the threshold for radiation damage in tissues both proximal and distal to the isocentric target, i.e., where the microbeams do not overlap. These factors make it possible to effectively irradiate a target using a field of many well defined, closely spaced microbeams.

The radiation beam for producing the microbeam array may be obtained from industrial X-ray generators or, more preferably, from synchrotron beamlines at electron storage rings. Most preferably, the radiation beam is obtained from a wiggler beam line at an electron storage ring. An exemplary beam source is the superconducting wiggler insertion device of the X17B beamline of the National Synchrotron Light Source. A conventional "planar" wiggler uses periodic transverse magnetic fields to produce a beam of rectangular cross-section, typically having a horizontal to vertical beam opening angle ratio on the order of 50:1. In an alternative embodiment, the radiation beam is obtained from a "helical" wiggler, a configuration capable of producing a substantially less anisotropic beam.

Synchrotron radiation is linearly polarized in the plane perpendicular to the direction of the magnetic fields generated by the wiggler. For most conventional planar wigglers, these fields are vertical, and the polarization is therefore in the horizontal plane. Since Compton scattering is lower in the direction of the polarization vector, horizontal beam polarization reduces scattering between the microbeams.

By lowering the scattering incident to the beam, the beam profile remains better defined, retaining a small penumbra, i.e., a sharper beam intensity fall-off, as it passes through tissue. The penumbra of the beam is the region at the periphery of the beam where the dose falls rapidly as a function of increasing distance from the center of the beam, measured perpendicularly to the beam axis at a given position along the beam path. The advantage of a small penumbra for X-ray fields is that it permits the protection of nearby radiation-sensitive organs. This protection is particularly pertinent to MRT, since the extraordinarily narrow microbeams and interbeam spacing must be precisely defined to take advantage of the capacity of brain tissue to recover over very small distances. In MRT, a large beam penumbra or shallow fall-off will vitiate the biological advantage of microscopic tissue regeneration by producing more beam overlap within the array.

The dose fall-off at the edge of any individual microbeam inside an array is preferably sharp enough at beam energies of between about 50 keV and about 300 keV, and at tissue depths of from about 1 cm to about 40 cm, to result in large "peak-to-valley" dose ratios (i.e., large ratios of the dose inside the geometrical envelope of a single microbeam to the doses between adjacent microbeams). Such large ratios allow dose planning so that the peak dose will be lethal to most dividing cells, while valley doses will be low enough to allow most normal cells to survive the radiation. The microbeam envelope is defined as the area through which a microbeam, or one or more than one microbeam pulses pass, and in which the absorbed dose of radiation will be lethal to the tissue.

The appropriate selection of the parameters of microbeam field configuration and peak dose is critical to the efficacy of microbeam radiation therapy. The peak dose along the microbeam axis and the center-to-center spacings of the microbeam envelopes must be appropriately selected to insure sufficiently low doses to tissue present in the valleys between the microbeams. The implemented combination of dose and configuration allows endothelial cells, oligodendrocytes (in brain tissue), and perhaps some other cells between the microbeams to divide and to repopulate tissues injured or ablated by the radiation treatment. Thus, unidirectional exposure does not permanently damage normal tissue, and the transient damage to some potentially mitotic cells does not affect the organism. By contrast, multiple exposure of the target at a cross-firing isocenter, irradiating the target volume without microscopic or macroscopic spatial interruption, causes irreparable damage to virtually all blood vessels and other structures within the target tissue. Such multiple irradiation of the target results in enhanced therapeutic necrosis of the target tissue.

Our observations of blood vessel regeneration indicate that endothelial cells cannot efficiently regenerate damaged blood vessels over distances on the order of thousands of micrometers (μm). In view of the known radiation pathology of normal blood vessels, the skilled artisan would optimally select microbeams as small as 50 μm to 200 μm in diameter. Therefore, microbeams useful for the present invention must have cross-sectional configurations such that substantially all non-target tissue within the microbeam envelope will be within the range of the migrating regenerating cells of the particular tissue. As a result, preferred microbeams are regular in cross-section, having a symmetrical geometry. Most preferred geometries include rectangular cross-sections, (bilateral symmetry) as well as radially symmetrical cross-sections such as circular or regular polygonal cross-sections.

The microbeams must have at least one cross-sectional dimension less than about 1 millimeter. Preferably, this dimension is between about 10 micrometers and about 500 micrometers. Most preferably the appropriate cross-sectional dimension is between about 20 micrometers and about 200 micrometers. For example, a preferred rectangular microbeam cross-section would have a short side of about 100 micrometers and another arbitrarily long side, on the order of several millimeters to several centimeters. In such a case the cross-section may be traversed by migrating cells at all points because of the symmetry of the rectangular cross-section and the small width of the rectangle.

Microbeam radiation therapy performed in accordance with the present invention employs at least two spatially distinct microbeams. Preferably, many more microbeams may be used. Generally, since a tumor is macroscopic, having dimensions in the range of millimeters to centimeters, several hundred or several thousand microbeams will be employed. When a group of microbeams are directed at a target from a single direction, the paths traversed by the microbeams may be described as a bundle. Within any bundle the microbeams may converge or diverge, but are preferably substantially mutually parallel. When viewed in cross-section, a microbeam bundle will present an array of individual microbeam cross-sections. Preferably these cross sections do not overlap.

The microbeam arrays useful in the present invention may be linear, rectangular, or otherwise regular in geometry. The linear array is the most preferred option when rectangular microbeams are employed. Specifically, a regular linear array of identical rectangular microbeam envelopes is preferably formed so that the beams are oriented with their long sides substantially parallel to one another. Preferably the microbeams in a linear array are oriented so that their long cross-sectional dimension is substantially vertical relative to gravity. In the preferred linear array, the envelopes in cross-section appear to stand on end in an even row, separated by interbeam spaces. Such an array takes advantage of the inherently low scattering produced by the horizontal beam polarization generated by conventional planar wiggler sources. The planar microbeams preferably have a short dimension within the preferred range of microbeam widths. However, since planar microbeams allow tissue migration along this dimension, the longer dimension may be arbitrarily long, on the order of several millimeters to several centimeters.

Alternatively, the array may be rectangular, or otherwise 2-dimensionally regular. In a rectangular array, for example, the microbeam envleopes may be arranged to form regular columns and rows, each microbeam separated from the others by regular interbeam spaces. A rectangular or other 2-dimensional array is preferred when the envelopes are circular, square, or otherwise substantially radially symmetrical in cross-section.

The array may be created sequentially by irradiating a target with one or a small number of microbeams and then moving the patient in a rectangular translational displacement and irradiating another portion of the target. By a series of horizontal and vertial displacements a relatively large array of microbeams may be created. Stereotactic equipment having microprocessor control is presently within the technical skill of those practicing in the art. Such equipment can manipulate a target with great accuracy and a precision of ± 1 micrometer. As a result very highly regular microbeam arrays may be created, taking advantage of the very small dimensons of each microbeam. A sequentially produced array is described in Examples 1 and 2.

Alternatively, the array may be produced simultaneously using a collimator having any of various designs known in the art. Such collimators have multiple radiation transmissive apertures allowing a bundle of regularly spaced microbeams to be directed at a target, simultaneously, by spatially fractionating a radiation beam having macroscopic cross-sections.

The array must position the envelopes so that they do not significantly overlap each other in non-target tissues. Since the envelopes in any array are preferably identical to one another in cross-section, the envelopes must have a minimum center-to-center spacing greater than the appropriate cross-sectional dimension of any individual envelope. The criterion cross-sectional dimension is the minimum width of a microbeam envelope, measured orthogonally to the beam path. The minimum center-to-center spacing is determined along the same line used to measure the cross-sectional dimension.

The microbeams are preferably spaced over intervals greater than the above-defined minimum interbeam spacing to allow the regeneration of tissue. The interbeam spacing may be empirically chosen to optimize the radiation field, depending upon the histological nature of the tissue being irradiated.

The optimum interbeam spacing in any application is also dependent upon the microbeam dose profile. Microbeams having sharper dose fall-off may be spaced more closely, while microbeams having broader profiles must be spaced more widely to achieve a tissue sparing effect. The spacing between microbeam envelopes is dependent upon microbeam profile. The spacing may be determined by calculating the distance between microbeams necessary for defining a peak-to-valley dose ratio that will enable the necessary regeneration of tissue. The maximum valley dose, i.e., the maximum dose that can be absorbed by interbeam tissue without tissue necrosis, is also dependent upon the histology of the tissue being irradiated, and may be optimized empirically.

The intensity of radiation at any point in the plane orthogonal to the path of a beam of X-rays, defining the dose fall-off, is a power function of the distance from the center of the beam path. The radiation dose to tissue, therefore, does not drop to background levels until significant distances are reached. The MRT technique takes advantage of the inherent resistance of tissue to radiation damage at doses slightly above background radiation levels. The microbeams are positioned at center-to-center distances such that at least some tissue between the beams is exposed to a summed, absorbed dose, that is less than the tissue's survivability threshold. Therefore, even though the radiation field is continuous within the microbeam array, the radiation intensity of the field is variable, and the destructive effect of the field is confined to discrete regions, within the microbeam envelopes. In this manner the field is spatially fractionated. As long as some tissue between the microbeams receives doses below its survivable threshold, the microbeam envelopes in a field are not overlapping.

The minimum center-to-center spacing is the distance at which the minimum dose generated within two adjacent microbeam envelopes exceeds the maximum survivable dose for the tissue. The preferred center-to-center spacing, as a result, must be greater than the minimum center-to-center spacing, allowing the minimum dose created by the adjacent microbeams to fall below the threshold survivable dose.

To achieve maximum irradiation of tissue within the microbeam field, the microbeam envelope center-to-center spacing must be minimized without compromising tissue sparing. At the same time the cross-sectional dimensions of the envelopes must be maximized, also without exceeding the limits of cellular migration that is characteristic of the tissue. As mentioned previously, the cross-sectional area of an envelope is defined as the region within which the microbeam dose intensity exceeds the maximum tolerable dose of the particular tissue. As center-to-center spacing of the envelopes is decreased, beam overlap will increase, thereby increasing the minimum radiation intensity within the field. Since this intensity must not exceed the maximum intensity survivable by the tissue and since the volume of tissue receiving this maximum dose must be sufficient to allow regeneration of non-target tissues, the envelope area must be decreased as center-to-center spacing decreases. It is therefore preferred that the intensity fall-off of the microbeams be very steep. In part, a steep fall-off permits the maximum density of microbeams per unit area of the microbeam field since there is less overlap between the microbeams. As a result, the threshold dose of the tissue in the interbeam spaces (radiation intensity minimum of the field) is not exceeded and

tissue sparing is not compromised even at extremely small center-to-center spacing.

The microbeam envelopes are preferably arrayed paraxially, which is defined as substantially mutually parallel. However, the microbeams may be generated so as they pass toward the target, they diverge from one another or converge to an isocenter. If the microbeams are not arrayed paraxially then it is preferred that the microbeams are spaced at intervals sufficient to avoid irreparable damage to normal tissues at any point along their paths. If the microbeams are convergent it is preferred that the valley dose of the field not exceed the maximum dose tolerated by the non-target tissue until at or near the limits of the target volume. More particularly, the maximum tolerated dose should not be exceeded in tissue proximal or distal to the target volume. The convergent microbeam envelopes should not overlap except within the target volume.

Similar considerations apply to the choice of angles when MRT is performed in the cross-firing mode in accordance with the present invention. In the cross-firing mode, the angular displacement of the microbeam bundles must be sufficient to ensure that the maximum tolerated dose is not exceeded in tissues proximal and distal to the target volume. By the same token, each microbeam bundle must be angularly displaced sufficiently from the others to ensure that the arrays do not overlap except at regions close to or within the target volume.

When parallel, cylindrical 25 μm diameter microbeams are spaced at 200 μm intervals, only about 1.2% of the tissue enclosed by the outer envelope of the microbeam array is directly irradiated. The majority of the tissue remains unirradiated. It is more difficult, therefore, to achieve major geometrical irradiation coverage of a clinically significant target by crossfired bundles of parallel cylindrical microbeams. Thus, for MRT, arrays of cylindrical or other radially symmetrical microbeams would not be preferred unless the microbeams were non-parallel, converging toward the target.

On the other hand, a bundle of parallel, 25 μm wide planar microbeams spaced at 200 μm center-to-center intervals, provides much more irradiation coverage, i.e., about 12.5%, than the array of cylindrical microbeams described above, yet such a bundle of planar microbeams is estimated to provide nearly as much tissue sparing. This unexpectedly beneficial result is due to the much smaller peak-to-valley absorbed dose ratios characteristic of the array of planar microbeams.

The efficacy of MRT is in part a function of the extraordinary precision of the beam spacing and the extraordinary narrowness of the microbeams themselves. Should the microbeam effect be smeared by movement of the surrounding tissue into the path of the beams, the benefit gained by the extreme narrowness of the beams would be attenuated, if not vitiated. Random or intentional macromotion of the patient will cause motion on a comparatively large scale, which can completely negate the tissue sparing effect of MRT. For this reason MRT is most preferably performed in conjunction with stereotactic apparatus to reduce or preferably eliminate such macromotion. However, even when the patient is stereotactically immobilized other sources of tissue motion remain. In particular, tissue micromotion is induced by physiomechanical cycles such as cardiac pulsation and pulmonary or respiratory cycles. MRT is therefore preferably performed in a pulsed mode, the pulsations of the microbeams coinciding with the rhythmic displacements of the target tissue resulting from the relevant physiomechanical rhythms. To limit such smearing the microbeam exposure may be pulsed to intersect with the appropriate tissue segment in harmony with the physiomechanical displacement of the tissue. An electromechanical oscillating shutter or similar device may be used to confine the irradiation period to a particular segment of the cardiac cycle and/or the respiratory cycle, the oscillation frequency varying in response to variations in the cycle frequency.

While MRT according to the present invention may be performed in synchrony with a physiomechanical cycle, it is also possible to perform MRT in a pulsed mode without regard for any physiomechanical cycle. The pulses may have durations ranging from about 20 milliseconds to about 2 seconds, depending on the energy of the X-ray source and the dose desired to be delivered.

In using microbeam radiation therapy to treat brain or spinal cord tumors, the irradiation is most preferably carried out in a pulsed mode. In this mode, the pulses are synchronized with the electrocardiogram. The exposure is limited to a small time interval of the heartbeat period, to avoid the smearing of the microbeam effect by pulsation caused by the cardiogenic pulsation of arteries in and near the brain or spinal cord. The portion of the cardiac contraction cycle selected for pulsed irradiation may be associated with minimum velocity or minimum acceleration of the brain or spinal cord vasculature. Based on our understanding of central nervous system blood circulation, it is believed that the optimal irradiation pulse may be at or near the T wave of the electrocardiogram, during diastole. However, the cardiosynchronous pulsation need not be limited to any specific portion of the cardiac cycle. An electromechanical oscillating shutter or a continuously rotating shutter may be used to confine the irradiation period to any desirable segment of the cardiac cycle. Either the frequency of oscillation of the shutter or the angular velocity of rotation of the shutter may be synchronized with electrocardiograph signals through a computer or microprocessor to effect the desired pulsation of irradiation. In one embodiment, a continuous recording of the electrocardiogram linked to an analog-to-digital converter may be used, so that the electrocardiograph voltage are recorded numerically in computer memory. A compute program would then act to determine the time of maximum voltage during the T-wave. The electromechanical shutter would open within several hundredths of a second after the maximum voltage to allow one pulse of microbeam radiation to the target.

In all immobilized parts of the body, except in those within the thorax and abdomen, the principal motions of tissues are synchronous with the heartbeat. In the thorax and abdomen, however, the principal motions are synchronous with the respiratory cycle. The method of the present invention, therefore, may further comprise the use of radiation pulses in synchrony with either the cardiac or the respiratory cycle, or in part with both cycles. Synchronization would depend on the anatomic site of the target and the complex patterns of physiomechanically cyclic micromotion and macromotion of the target. This aspect of the present invention is particularly important to spare the lung from radiation-induced pneumonitis when irradiating a target deep in the thorax, whether in the lung, the mediastinum, the thoracic paravertebral and vertebral tissues, or the heart itself. In these circumstances, the sparing effect of mi-

crobeams may be attributable to sparing of radiation-sensitive epithelial cells that line the alveolar air spaces, as well as the sparing of endothelial cells that line pulmonary blood vessels. MRT may, therefore, be applicable to palliative and possibly curative radiation therapy of lung and esophageal cancers, which are common causes of prolonged illness in elderly patients.

The following examples further illustrate the present invention. In the Examples X-ray radiation generated by a wiggler beam line at a synchrotron was collimated to a rectangular microbeam 30 μm wide. The collimator comprises a circular disk of tantalum 0.5 inches in diameter and 0.25 inches thick that has been cut in half along a diameter and fixed in a frame leaving the two halves of the disk separated by a space of 30 μm through which the microbeam was passed. The height of the X-ray beam was limited by a larger beam aperture so that the microbeam height was 4 mm. The X-ray energy was filtered through a 0.2 mm thick gadolinium filter producing a median beam energy of about 50 keV,. with 90% of the photons having energies between 30 and 130 keV.

Planar microbeams with heights greater than 4 mm were generated in the following manner: After each exposure to a single microbeam, the subject being irradiated was laterally translocated a desired distance by means of a microprocessor controlled stereotactic device. The subject was then irradiated with the microbeam producing the desired dose. The parallel planar microbeams are thereby easily produced in any desired number with any desired center-to-center spacing. By vertically translocating the experimental subject 4 mm and irradiating at positions identical to the first array microbeams 8 mm high were produced. This vertical translocation step was repeated to produce microbeams up to 12 mm in height.

EXAMPLE 1

Our experiments have shown that X-ray irradiation of 30 μm-wide brain slices having 4–16 mm-high, rectangular cross-sections with peak doses up to at least 625 Gy does little or no permanent damage to the normal rat brain when the slices are in multiple (40–80) parallel planes separated at 100–200 μm center-to-center intervals. Monte Carlo computations for an adult human head phantom (Slatkin et al , . "Microbeam Radiation Therapy", *Medical Physics*, 19(6), (1992)) have indicated how one may exploit microbeams for human radiotherapy by using a cross-fire technique with the target tumor at the cross-fire isocenter. Our recent studies of the degree of tumor growth-inhibition provided by multiple, parallel, unidirectional microbeams unexpectedly and very encouragingly resulted in long-term growth control of nearly half of the malignant rat brain tumors treated with one of the two MRT protocols tested. These protocols were developed for microbeam irradiation of a standard 4 mm diameter malignant right frontocerebral rat brain tumor (9L gliosarcoma of the right frontal lobe 14 days after right frontocerebral injection of 10^4 viable tumor cells suspended in 1 μl of medium). The radiation employed was X-ray radiation generated at a wiggler beam line at a synchrotron. The X-ray radiation had beam energies in the range of 30–130 keV.

Protocol A: 625 Gy incident upon a series of forty parallel 30 μm-wide, 16 mm-high anteroposterior head slices, each narrow slice of directly irradiated head tissue separated from adjacent directly irradiated, virtually parallel slices by 200 μm center-to-center.

Protocol B: 625 Gy incident upon a series of forty parallel 30 μm-wide, 16 mm-high anteroposterior head slices, each directly irradiated slice separated from adjacent directly irradiated, virtually parallel slices by 100 μm center-to-center.

Protocol A resulted in about 70% reduction in clonogenic tumor cell survival. This determination was made through counting those surviving tumor cell clones that had an arbitrary standard minimum rate of growth in vitro. Protocol A also produced a twofold extension of the median postirradiation day of death, from 5 days for seven unirradiated, matched, brain-tumor-bearing control rats, to 10 days for six irradiated tumor-bearing rats.

Protocol B resulted in about 98% reduction of clonogenic tumor cell survival. Protocol B also produced a fourfold extension of the median postirradiation day of death, from 5 days for the control rats, to 20 days for seven irradiated rats. Analysis of the weight changes in these rats together with their post-irradiation survival times using the 'morbidity index' method (Coderre et al., *Radiay Res.*, 128, 177–85, 1991) of non-parametric analysis indicated a highly significant (>99.5% confidence level) palliative effect of Protocol B even with the small numbers of rats used for the study. More remarkable was the 30-fold extension in the lifetimes of the three long-term surviving rats in the 100 μm group, in comparison with the 5-day median life expectancy of the untreated rats. Protocol B animals, five months after irradiation, showed no obvious neurological deficits. Indications of the radiation treatment of malignant brain tumor in these rats included loss of some fur on the right side of the head associated with subacute blepharitis. Four months after radiation, cataract in the right eye was observed in all three survivors. Also, right frontocerebral cystic gliosis was detected by magnetic resonance imaging (MRI) 68 days post-irradiation.

EXAMPLE 2

Further evidence of the palliative effect of unidirectional microbeam radiation therapy was obtained shown by the following experimental investigation of cerebral tumors in rats.

Using a protocol similar to that described in Example 1, 7 rats were given left frontocerebral injections of 10^4 viable 9L gliosarcoma cells. In this well established protocol, median survival is 20 days ±3 days. At 17.5 days after implantation of the tumor, the tumor normally has advanced to a mass of about 175 mg.

The 7 rats received irradiation according to the following protocol: Each rat was irradiated in an anteroposterior direction using an array of vertical planar microbeams, produced sequentially. Each microbeam was 30 μm wide and 4 mm high. After each exposure, the rat being irradiated was moved 100 μm to one side by a microprocessor controlled stereotactic device, thereby producing 100 μm center-to-center spacing between microbeams. The exposures began at 4 mm to the right of the midline, proceeding to the left side of the animal, ending at 12 mm to the left of the midline. On completion of this series of exposures, the animal was elevated by 4 mm and a second series of exposures was commenced proceeding from the left side to the right side of the animal. Finally a third series of exposures was performed proceeding right to left after the animal was raised an additional 4 mm. Therefore the

array of microbeams produced by this protocol was 16 mm wide and 12 mm high.

The rats were divided into two groups according to the peak dose of the microbeams in each arrray. Group I (4 rats) received microbeams having a peak dose of 337.5 Gy, while Group II (3 rats) received microbeams having a peak dose of 225 Gy.

Notwithstanding the extraordinarily late stage of the tumor progression, an unexpected palliative effect was observed as measured by survival of the rats. Rats from Group I exhibited a median survival of 10.5 days post-irradiation, with an average survival of 9.5 days. This is equivalent to a four-fold extension of survival. Rats of Group II showed median survival of 3 days, with an average survival of 6.3 days. Given the stage of tumor progression at the time of irradiation, median survival is expected to be approximately 2.5 days.

EXAMPLE 3

In this example, microbeam radiation therapy in a cross-firing mode was demonstrated by computer modelling the irradiation of a human head phantom with X-ray microbeams fired from several angles. The human head phantom was a 16 cm diameter, 16 cm high cylindrical water target, believed to approximate the size and density of a human head target. Each microbeam bundle was composed of 150 substantailly parallel planar microbeams. Each microbeam was 25 μm wide and 30 mm high. The center-to-center spacing of the microbeams was 200 μm. Therefore the microbeam bundles being modelled had cross-sections of 3 cm ×3 cm.

Using computer codes capable of calculating the scattering of electrons and the dispersion of X-ray radiation, 8 cross-fired bundles of 100 key microbeams were found to produce an estimated >48 Gy average absorbed dose at a 7.5 cm deep target with ≦2.9 Gy interbeam absorbed doses at tissue proximal and distal to the target. If it is accepted that the minimum threshold dose for irreversible morphological damage from irradiation of mature mammalian brain is on the order of 10 Gy, the 2.9 Gy interbeam absorbed dose would avoid tissue necrosis in non-targeted zones.

Thus while we have described what are presently the preferred embodiments of the present invention, other and further changes and modifications could be made without departing from the scope of the invention, and its is intended by the inventors to claim all such changes and modifications.

We claim:

1. A method of performing radiation therapy on a patient comprising the step of

irradiating a target tissue with a therapeutic quantity of high energy electromagnetic radiation from a radiation source through at least two substantially mutually parallel spatially distinct microbeam envelopes, each envelope describing a path having a width less than about i millimeter, wherein the target tissue within the microbeam envelope receives a summed absorbed dose of radiation exceeding a maximum absorbed dose survivable by the target tissue and non-target tissue between adjacent microbeam envelopes receives a summed absorbed dose of radiation less than a minimum absorbed dose lethal to non-target tissue thereby permitting irradiated non-target tissue to regenerate.

2. The method of claim 1, wherein said irradiating further comprises said microbeam envelope path width being between about 10 micrometers and about 500 micrometers.

3. The method of claim 1, wherein said irradiating further comprises said microbeam envelope path width being between about 20 micrometers and about 100 micrometers.

4. The method of claim 1, wherein said irradiating further comprises said microbeam envelope having a rectangular cross-section.

5. The method of claim 4, wherein a side of the rectangular cross-section is from about 20 micrometers to about 100 micrometers.

6. The method of claim 1, wherein said irradiating further comprises said microbeam envelope having a substantially radially symmetrical cross-section.

7. The method of claim 6, wherein the microbeam envelope has a substantially circular cross-section.

8. The method of claim 7, wherein the microbeam envelope cross-section has a diameter of from about 20 micrometers to about 100 micrometers.

9. The method of claim 1, wherein the radiation is monochromatic.

10. The method of claim 1, wherein the radiation is generated by a synchrotron.

11. The method of claim 10, wherein the radiation is generated by a wiggler insertion device.

12. The method of claim 1, wherein said irradiating further comprises generating a microbeam bundle, which has a plurality of spatially distinct microbeam envelopes.

13. The method of claim 12, wherein generating the microbeam bundle comprises generating a substantially regularly spaced array of microbeams envelopes.

14. The method of claim 13, wherein the array is substantially linear.

15. The method of claim 13 wherein the array is 2-dimensional.

16. The method of claim 15 wherein the array is substantially rectangular.

17. The method of claim 15, wherein the array is substantially radially symmetrical.

18. The method of claim 17, wherein the array is substantially circular.

19. The method of claim 12, wherein the microbeam envelopes of said microbeam bundle have a center-to-center spacing of from about 50 micrometers to about 500 micrometers.

20. The method of claim 12, wherein the microbeam bundle envelopes of said microbeam bundle have a center-to-center spacing of from about 50 micrometers to about 200 micrometers.

21. The method of claim 1, wherein the irradiating further comprises producing the microbeams simultaneously.

22. The method of claim 1, wherein the irradiating further comprises producing the microbeams in temporally discrete radiation pulses.

23. The method of claim 12, wherein said irradiating further comprises producing a plurality of microbeam bundles.

24. The method of claim 23, wherein the microbeam bundles are substantially mutually parallel.

25. The method of claim 24, wherein the microbeam bundles are rectangularly translationally displaced from each other and substantially mutually parallel.

26. The method of claim 23, wherein the microbeam bundles are angularly displaced from each other and substantially isofocused and mutually convergent.

27. The method of claim 12, wherein said irradiating further comprises generating each microbeam bundle in a single radiation pulse.

28. The method of claim 12, wherein said irradiating further comprises generating each microbeam bundle by delivering a plurality of temporally discrete radiation pulses.

29. The method of claim 28, wherein said plurality of radiation pulses irradiate the target tissue with substantially identical microbeam envelopes.

30. The method of claim 28, wherein the radiation pulses irradiate said target tissue with rectangularly translationally displaced microbeam envelopes.

31. The method of claim 28, wherein the radiation pulses have substantially regular durations and substantially regular interpulse intervals.

32. The method of claim 31, wherein the radiation pulses have a duration of from about 20 milliseconds to about 2 seconds.

33. The method of claim 31, wherein the radiation pulses have durations and interpulse intervals substantially synchronized with a physiomechanical cycle of the patient.

34. The method of claim 33, wherein the physiomechanical cycle is a cardiac cycle.

35. The method of claim 33, wherein the physiomechanical cycle is a pulmonary cycle.

36. The method of claim 33, wherein the physiomechanical cycle is a cardiopulmonary cycle.

37. The method of claim 1, wherein the radiation is focused.

38. The method of claim 1, wherein the radiation is unfocused.

39. The method of claim 1, wherein the target is a tumor.

40. The method of claim 39, wherein the tumor is intracranial.

41. The method of claim 1, further comprising stereotactically immobilizing the patient.

42. The method of claim 1, wherein the radiation is X-ray radiation.

43. The method of claim 42, wherein the radiation has a beam intensity within a range of from about 30 key to about 300 keV.

44. The method of claim 42, wherein the beam intensity is within a range of from about 50 keV to about 150 keV.

* * * * *

United States Patent [19]

Segall

[11] **4,215,274**

[45] **Jul. 29, 1980**

[54] **X-RAY DETECTOR WITH PICOSECOND TIME RESOLUTION**

[75] Inventor: **Stephen B. Segall**, Ann Arbor, Mich.

[73] Assignee: **KMS Fusion, Inc.**, Ann Arbor, Mich.

[21] Appl. No.: **863,941**

[22] Filed: **Dec. 23, 1977**

[51] Int. Cl.² **G01T 1/20**

[52] U.S. Cl. ..... **250/361 R; 250/368**

[58] Field of Search ..... 250/361 R, 368, 362, 250/397, 363, 369

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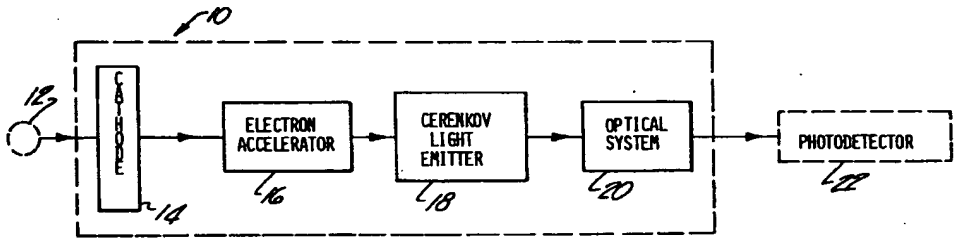
Primary Examiner—Bruce C. Anderson

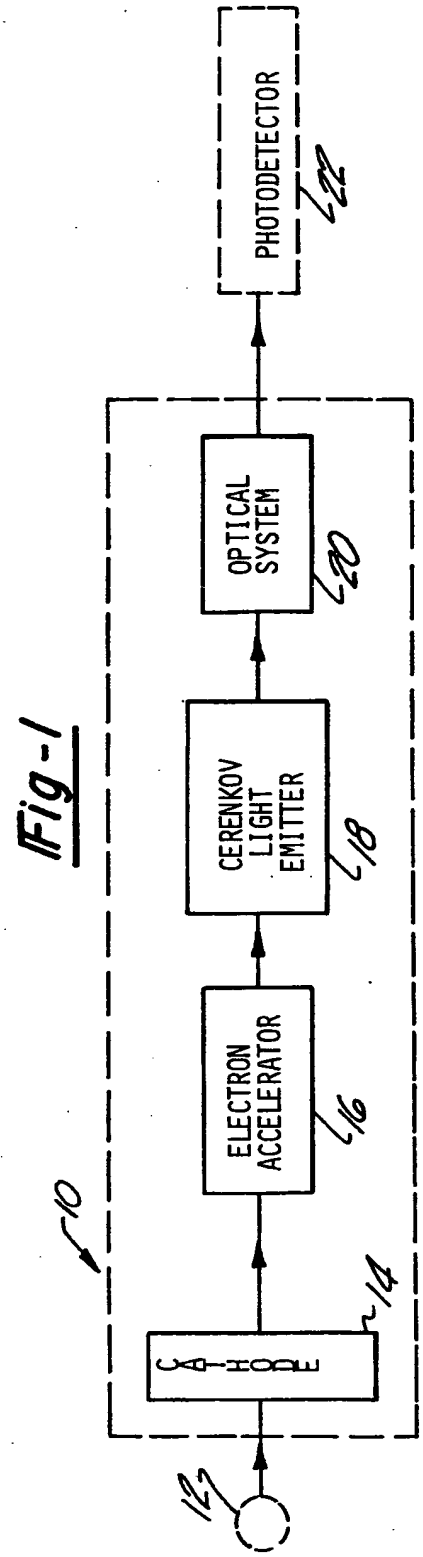
Attorney, Agent, or Firm—Barnes, Kisselle, Raisch & Choate

[57] **ABSTRACT**

An X-ray detector for obtaining time resolved signals from intense pulsed X-ray sources, such as from a fuel pellet during a laser fusion process. The detector has a cathode which emits electrons when bombarded by X-rays from the fuel pellet. The electrons are accelerated by an electron accelerator to relativistic velocities and impinge on a Cherenkov emitter which radiates light. An optical system collects and focuses the radiated light onto an image converter streak camera or other fast photodetector to provide a trace of the light intensity as a function of time. Time resolved images of the fuel pellet may be produced by the detector and recorded by an image converter streak camera or by a camera using an optical Kerr cell shutter.

42 Claims, 22 Drawing Figures




PHOTODETECTOR
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OPTICAL SYSTEM
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CERENKOV LIGHT EMITTER
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ELECTRON ACCELERATOR
16
CATHODE
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Fig-1

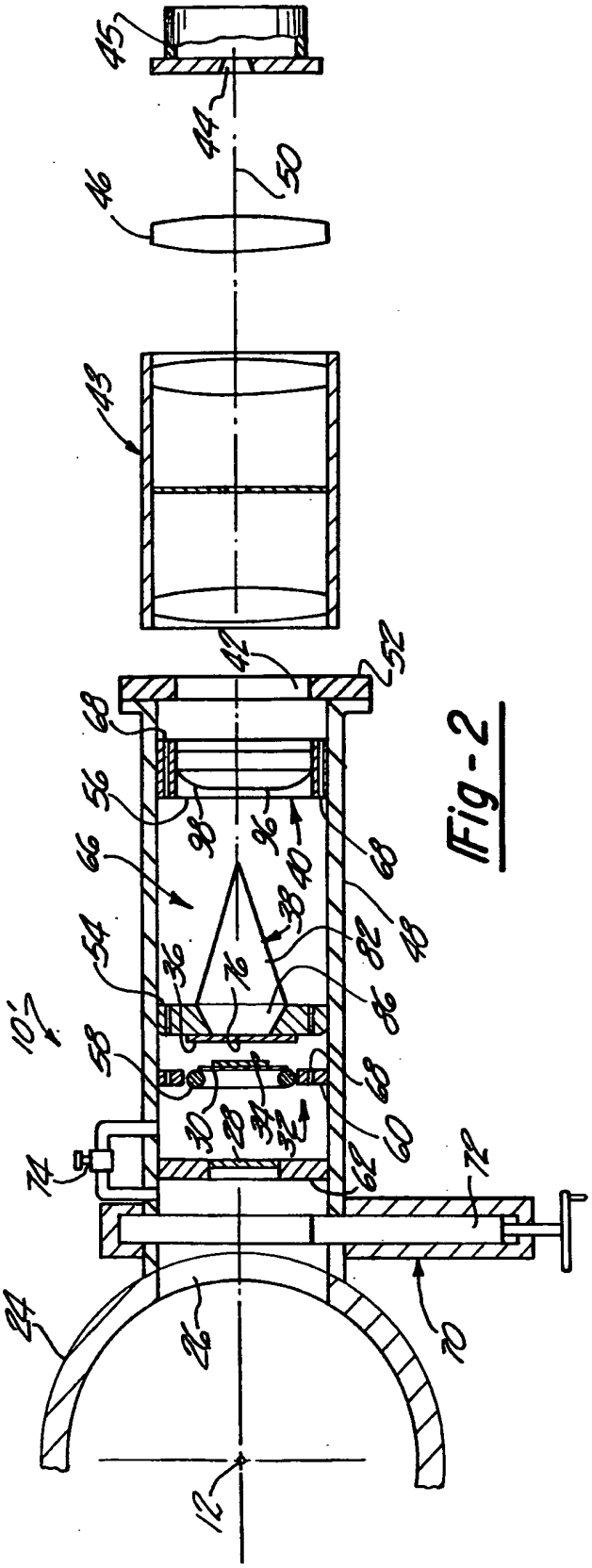
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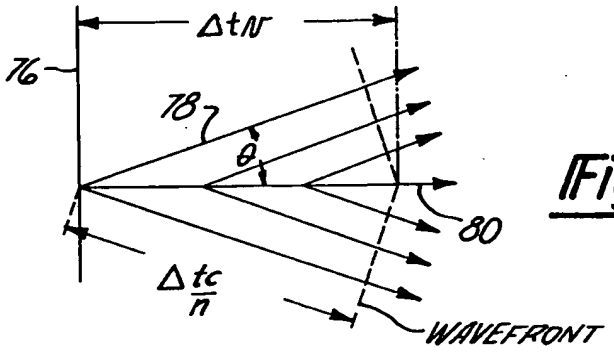
Fig-2



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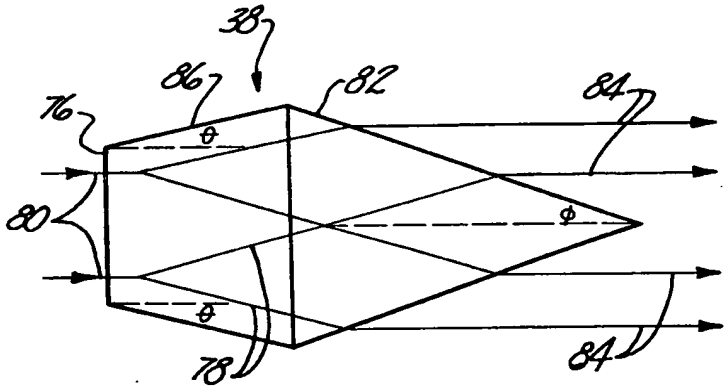

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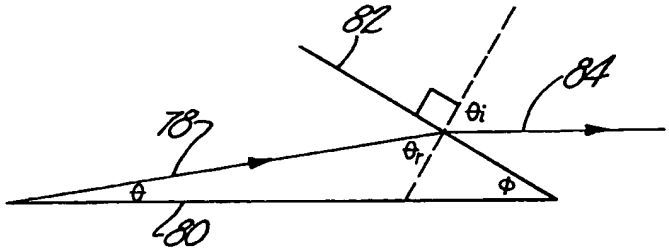

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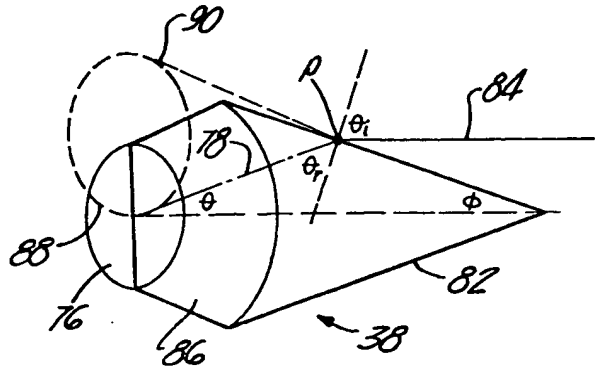

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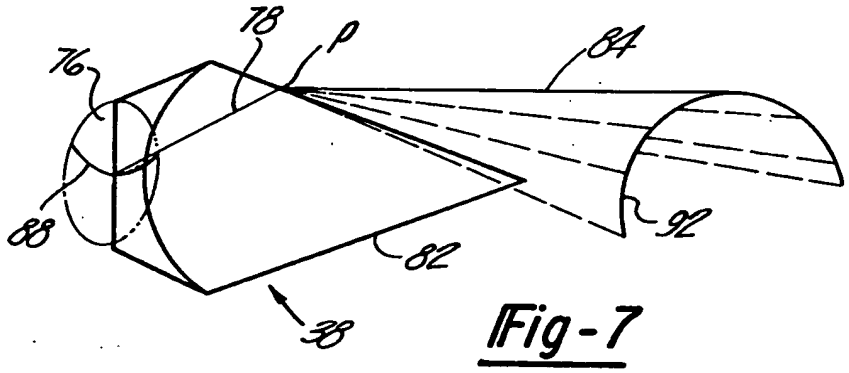

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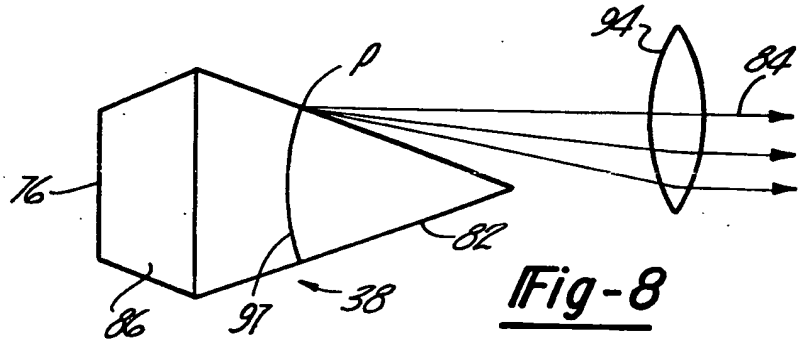

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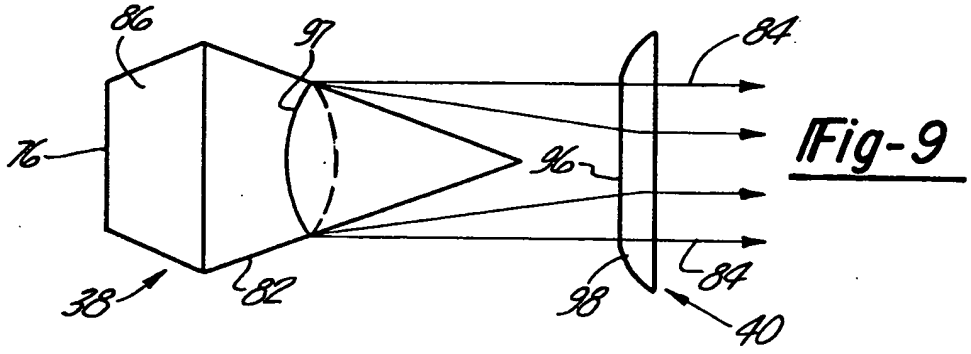

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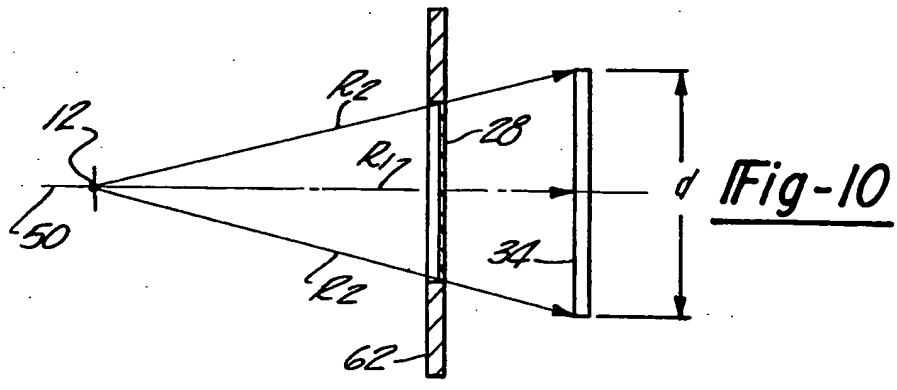

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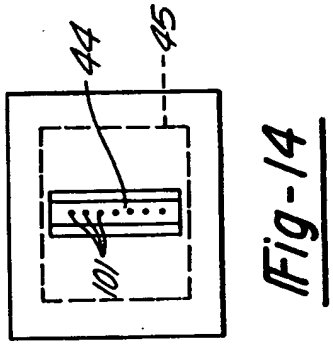

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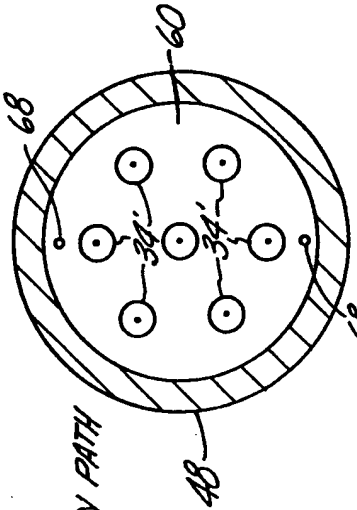

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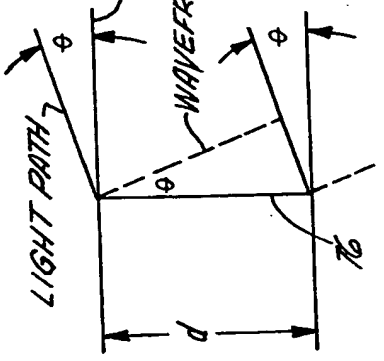

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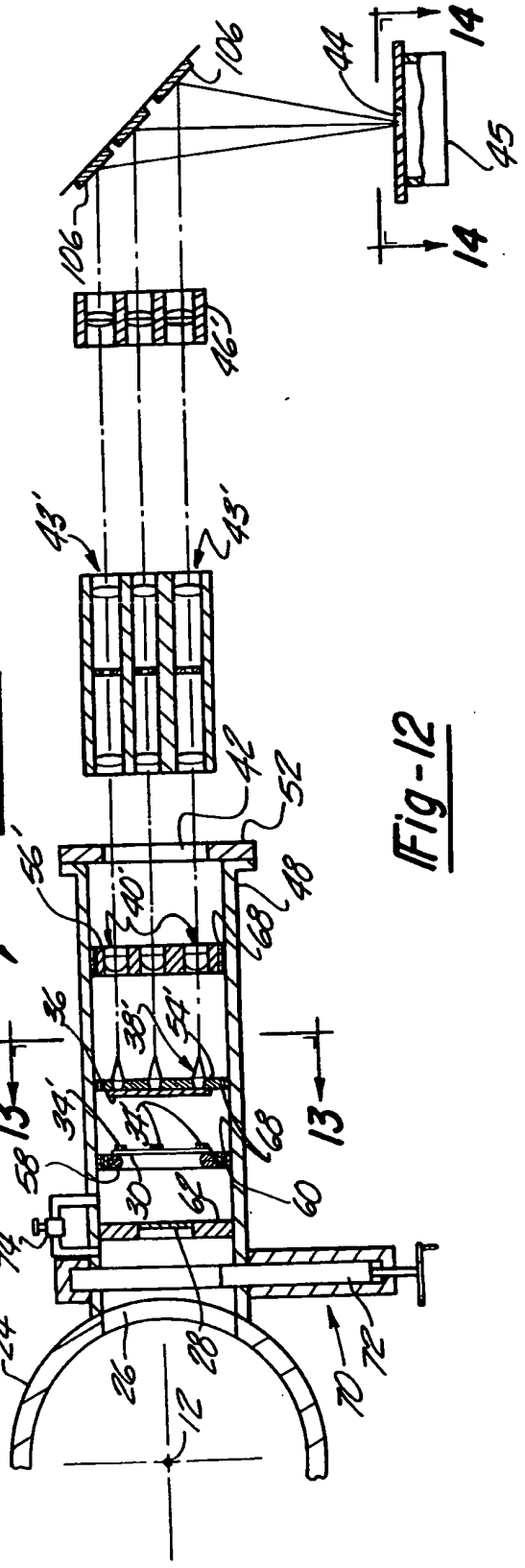

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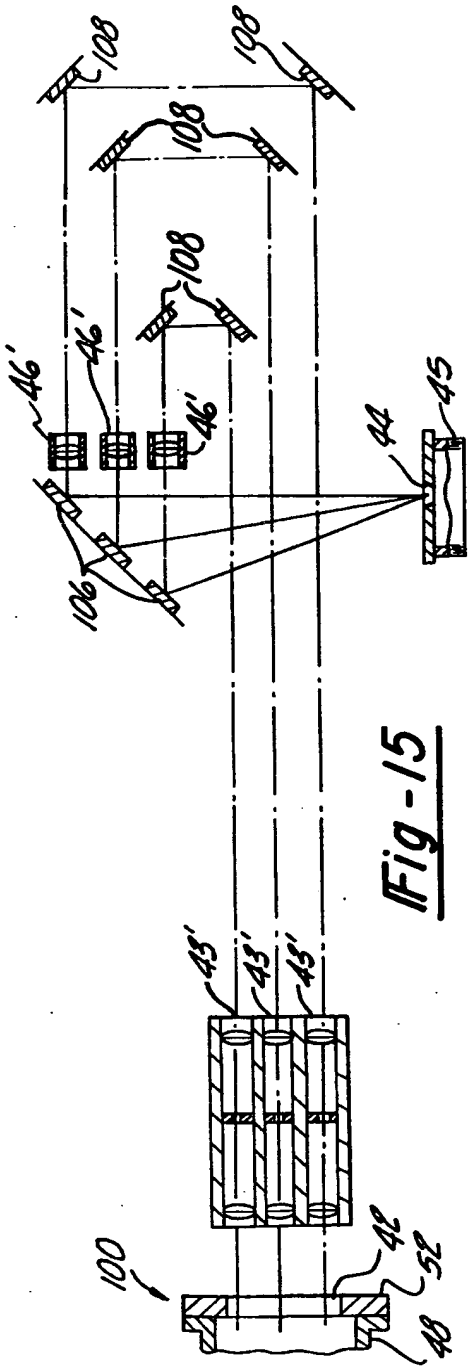
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Fig-15

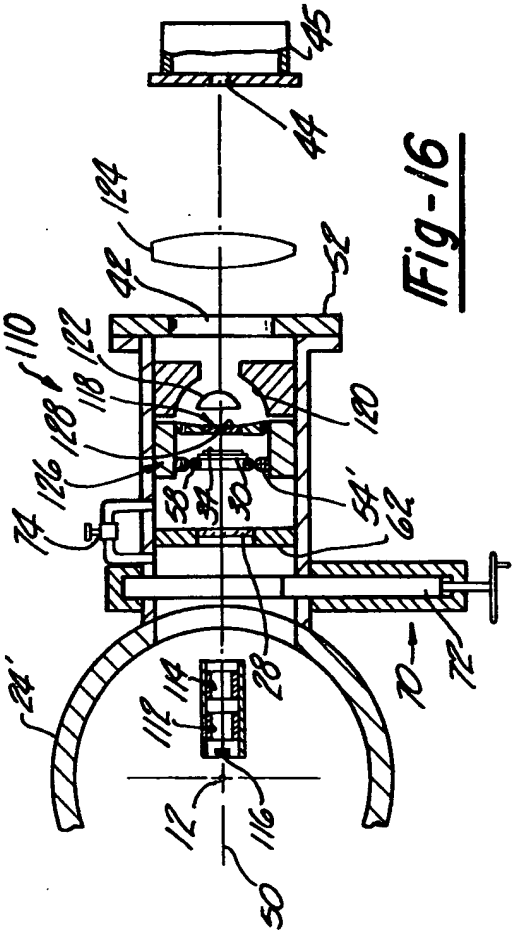
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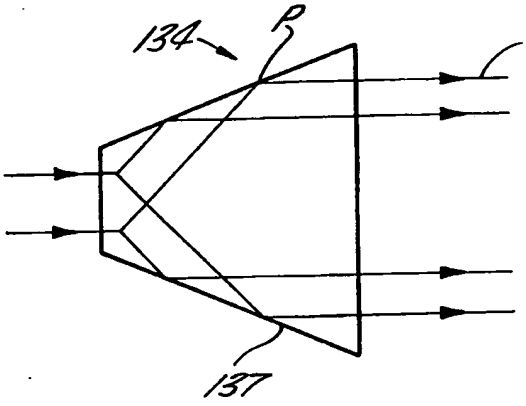
Fig-16



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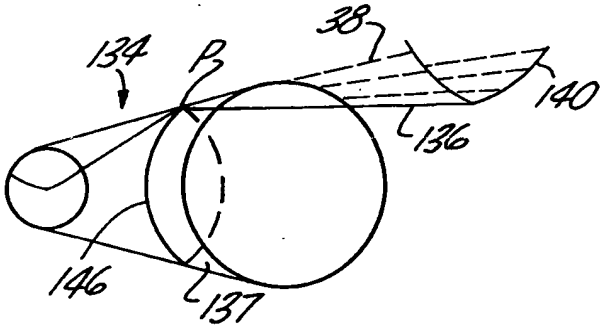

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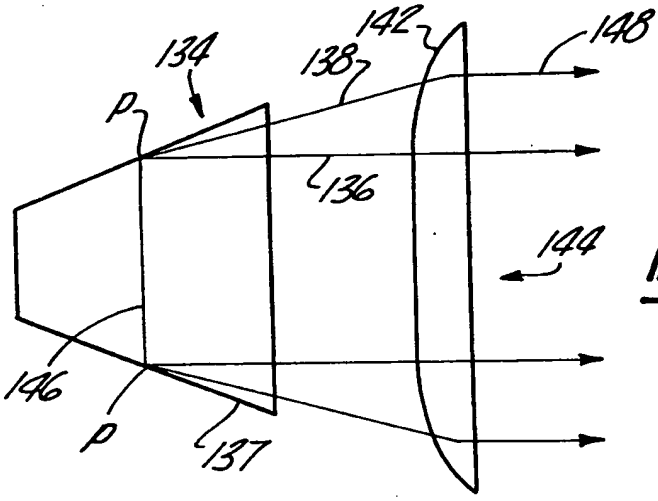

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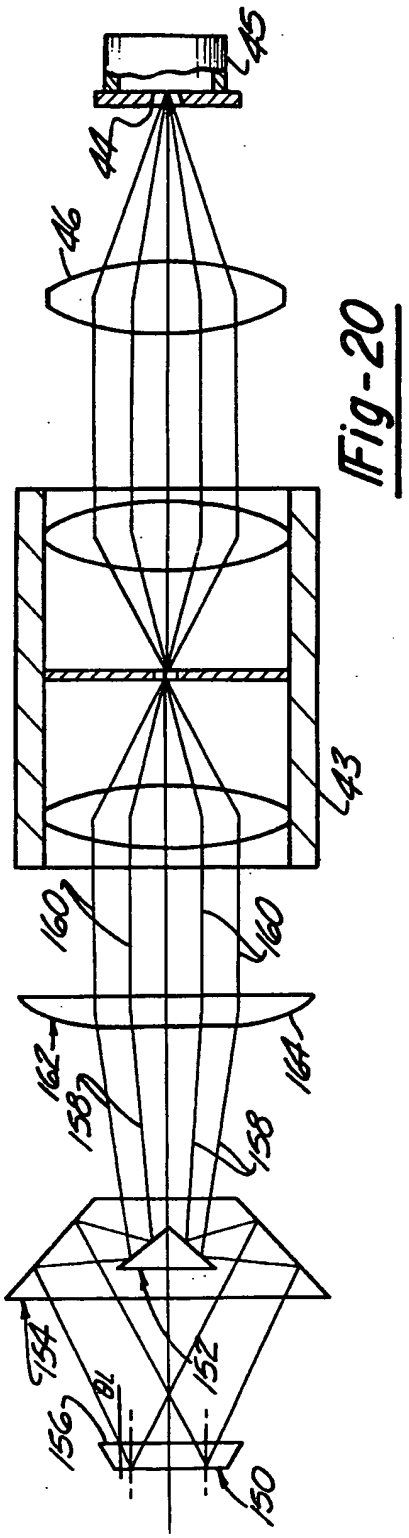

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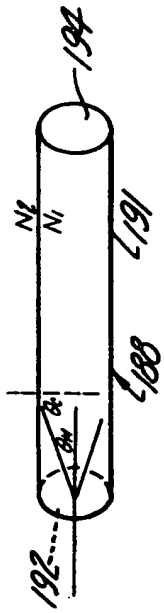

Fig-22

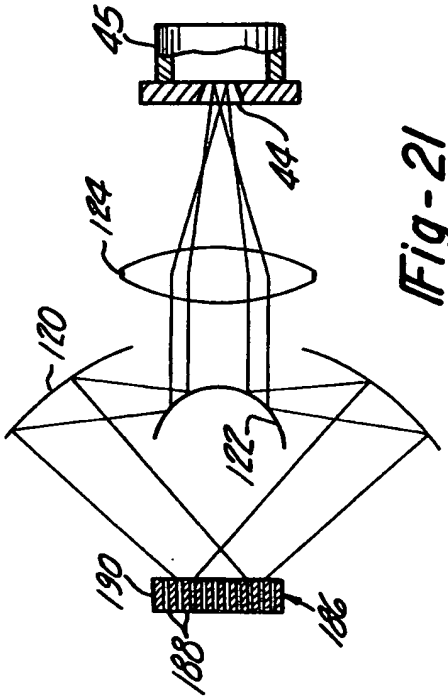

Fig-21

X-RAY DETECTOR WITH PICOSECOND TIME RESOLUTION

This invention relates to the time resolved detection of X-rays and charged atomic particles with particular application to the time resolved detection of X-rays emitted from the fuel pellet in a nuclear fusion reaction.

In a laser driven fusion process both the irradiation of the fuel pellet by the laser beam and the fusion reaction produce X-rays which, if monitored, will provide useful information about the manner in and conditions under which the laser fusion process occurs. When the fusion of the fuel in the pellet occurs, neutrons, alpha particles and other fusion products may also be produced which could be monitored to provide useful information about the manner in and conditions under which fusion occurs. However, neutrons and other fusion products are only produced at the peak of the implosion of a fuel pellet when fusion of the fuel occurs while X-rays are produced during the entire implosion process and even for a time after fusion of the fuel takes place and the pellet begins to disassemble. Thus, monitoring of the X-rays in a laser driven fusion process is believed to provide information on the development of instabilities in the imploding fuel pellet, the symmetry of the implosion, the velocity and temperature history of the imploding shell of the fuel pellet, and the temperature and density of the fuel in the pellet at peak compression.

The monitoring of X-rays is believed to provide this useful information even if fusion does not occur and, hence, when no neutrons or other fusion products are produced or when the number of neutrons produced is too small for obtaining useful information from the monitoring thereof. In order to analyze the various stages or steps of this laser fusion process, a detector device must have a time resolution on the order of ten picoseconds or less since the burst of X-rays from the fuel pellet at peak compression, during which time thermonuclear burn occurs, is only expected to last on the order of ten picoseconds to a few tens of picoseconds.

Objects of this invention are to provide an X-ray detector having a fast enough response time to enable time resolution of the quantity of X-rays produced by a laser driven fusion reaction process, determine the temperature and compression of the fuel pellet at various stages of the laser fusion process, and photograph time resolved images of the fuel pellet and plasma during the laser fusion process.

These and other objects, features and advantages of this invention will be apparent from the following description, appended claims and accompanying drawings in which:

FIG. 1 is a block diagram of an X-ray detector embodying this invention.

FIG. 2 is a semi-schematic side view in section of an X-ray detector embodying this invention mounted on a fusion reactor chamber and having a conical lens Cherenkov light emitter.

FIG. 3 is a diagram of Cherenkov emission of a conical wave front of light by a relativistic electron passing through a transparent material.

FIG. 4 is a diagram of rays of light emitted as Cherenkov radiation in a conical emitter lens of the X-ray detector of FIG. 2.

FIG. 5 is a diagram of the geometric relationship of the path of a relativistic electron in the conical emitter lens of FIG. 2 to the rays of light emitted by Cherenkov radiation therein.

FIG. 6 is a diagram of the locus of all rays of light emitted by relativistic electrons in the conical emitter lens of FIG. 2 at an angle ϕ to its optical axis which pass through a point P on the exit surface of the conical emitter lens.

FIG. 7 is a diagram of all of the rays of light leaving a point P on the exit surface of the conical emitter lens of FIG. 2 which were produced by Cherenkov emission in the lens at an angle ϕ to its optical axis.

FIG. 8 is a diagram of a lens refracting skewed rays of light emitted from a point P on the exit surface of the conical emitter lens of FIG. 2 into parallel rays of light.

FIG. 9 is a diagram of an optical element refracting skewed rays of light emitted from the exit surface of the conical emitter lens of FIG. 2 into parallel rays of light.

FIG. 10 is a diagram of the geometric relationship of the fuel pellet, aperture, and cathode of the detector of FIG. 2.

FIG. 11 is a diagram illustrating the different positions of the wave fronts of two rays of light emitted in the same plane as Cherenkov radiation from two spaced apart electrons entering the emitter lens of FIG. 2 at the same instant of time.

FIG. 12 is a semi-schematic side view in section of a modified X-ray detector embodying this invention mounted on a fusion reactor chamber and having multiple conical lens Cherenkov light emitters.

FIG. 13 is a cross sectional view on line 13—13 of FIG. 12 showing an end view of the array of multiple conical lens emitters of the X-ray detector of FIG. 12.

FIG. 14 is a plan view of the entrance slit of an image converter camera of the X-ray detector of FIG. 12 showing the light focused in a plurality of spots at the slit.

FIG. 15 is a diagram of an optical system for varying the path lengths of differnt beams of light produced by the X-ray detector of FIG. 12 in order to record a longer interval of X-ray emission from the fuel pellet while retaining the same time resolution.

FIG. 16 is a semi-schematic side view in section of a modified X-ray detector embodying this invention producing time resolved images of a fuel pellet emitting X-rays.

FIG. 17 is a diagram of rays of light emitted as Cherenkov radiation in a conical emitter prism.

FIG. 18 is a diagram of the locus of all the rays of light leaving a point P on the reflecting surface of a conical prism which were produced by Cherenkov radiation in the prism at an angle ϕ to its optical axis.

FIG. 19 is a diagram of an optical element refracting the skewed rays of light emitted from the exit surface of the conical emitter prism of FIG. 17 into parallel rays of light.

FIG. 20 is a diagram of an optical system utilizing conical mirrors to collect rays of light from a thin slab conical frustrum Cherenkov emitter.

FIG. 21 is a diagram of an optical system with a double reflecting mirror and lens system for reconstructing an image of a fuel pellet from the rays of light emitted by a fiber optic plate Cherenkov emitter and focusing the image on the entrance slit of an image converter camera.

FIG. 22 is a perspective view of one of the optical fibers of the fiber optic plate Cherenkov emitter of FIG. 21.

DESCRIPTION OF SINGLE SPOT INTENSITY DETECTOR

Referring in more detail to the drawings, FIG. 1 illustrates a block diagram of an X-ray detector 10 embodying this invention in which X-rays emitted from an irradiated fuel pellet 12 strike a metallic cathode 14 causing electrons to be emitted therefrom in accordance with the well-known photoelectric effect. The emitted electrons are accelerated to a velocity approaching the speed of light in a vacuum by an electron accelerator 16 and enter a Cherenkov emitter 18 which emits light, a sizable fraction of which is in the visible and near ultraviolet part of the spectrum. In a so-called Cherenkov emitter, if a charged atomic particle, such as an electron, moves through a transparent solid or liquid medium with a velocity greater than the velocity of light in the medium, nearby atoms of the medium are momentarily electrically polarized which disturbs the electric field of such atoms, thereby producing a transient dipole moment which causes emission of electromagnetic waves of light.

The light from the Cherenkov emitter 18 is collected and focused by a suitable optical system 20 onto a photodetector 22 with a rapid response time. A trace of the intensity of the light as a function of time and, hence, the magnitude of the X-ray emission from fuel pellet 12 as a function of time, may be produced by a photodetector such as an image converter streak camera. Optical system 20 may also be designed to reconstruct an image of the pellet which may be recorded by a suitable photodetector with a fast optical response time to provide a time and space resolved record of the image of the fuel pellet during various stages of the laser fusion process.

FIG. 2 illustrates an X-ray detector 10' embodying this invention mounted on a laser fusion reactor chamber 24 with a fuel pellet 12 therein. X-rays emitted by fuel pellet 12 pass through a vacuum port or exit aperture 26 in reactor chamber 24 and into detector 10' through an X-ray transmitting aperture and window 28 separating the low vacuum of the target chamber from the high vacuum of the X-ray detector. The X-rays pass through one plate 30 of a parallel plate capacitor accelerator 32 and impinge on a cathode 34 which emits electrons. The electrons emitted from cathode 34 are accelerated between plates 30 and 36 of the parallel plate capacitor which is supplied with a high potential by either a pulsed high voltage source such as a Marx generator or by a direct current high voltage power supply. The electrons accelerated by parallel plate capacitor 32 pass through plate 36 thereof and bombard a Cherenkov emitter in the form of a conical lens 38. A fraction of the light from conical emitter lens 38 is collected and emitted as substantially parallel rays by a lens 40 and passes from detector 10' through a plane window 42. The light from detector 10' passes through a pinhole spatial filter 43 which removes nonparallel components of the light and is collected and focused to a spot at the entrance slit 44 of an image converter camera 45 by an optical focusing system represented by converging lens 46. Filter 43 is optional for a single spot detector since entrance slit 44 removes nonparallel rays which extend generally perpendicular to the longitudinal length of the slit so that such nonparallel rays do not reach camera 45.

Light passing through entrance slit 44 impinges on a cathode of image converter camera 45 and causes the cathode to emit a flux of electrons. When camera 45 is operated in the streak mode, this flux of electrons is swept across a fluorescent screen to produce a trace of light as a function of time. The intensity of this trace of light is proportional to the intensity of the light focused on entrance slit 44. An image intensifier is used with camera 45 to amplify or increase the intensity of the trace of light produced by camera 45 so that such trace of light can be recorded on sensitive photographic film. Other examples of photodetectors which it is believed may be used to detect the light emitted from picosecond X-ray detector 10' are cameras using optical Kerr cell shutters actuated by picosecond laser pulses such as those developed by M. A. Dugay and J. W. Hansen at Bell Telephone Laboratories and described in Applied Physics Letters 15, 192 (1969) and picosecond photocathode ray tubes such as those developed by C. Lotz and G. Clement at the Laboratories d'Electronique et de Physique Appliquee, and described in the May, 1974 issue of electro Optical Systems Design. All of these photodetectors are believed to have a response time of less than fifty picoseconds and are believed to be capable of a response time on the order of ten picoseconds or less. These response times are needed to detect the quantity as a function of time of the X-rays produced by a laser driven fusion reaction or to record time resolved images of the fuel pellet and plasma during the laser fusion process.

Cathode 34 is a thin layer of a material with a high atomic number, Z, such as titanium, nickel, tin or gold deposited on the face of accelerator plate 30 farthest from fuel pellet 12. By selecting different high Z materials with different X-ray K edges for the cathode, the detector may be made responsive to different portions of the spectrum of X-rays emitted from fuel pellet 12. The quantity of electrons produced by the cathode 34 may be maximized for a given X-ray spectral distribution by selection of the appropriate material for the cathode and the thickness thereof. Selective spectral sensitivity can also be achieved by coating the cathode with a single high atomic number material such as gold and placing thin attenuating filters of various materials in front of window 28. Alternatively, selective filter pairs could be made by filtering the incoming signal with one absorber and selecting the deposited cathode material to preferentially absorb a narrow spectral band of the filtered signal entering the detector.

In detector 10', window 28, cathode 34, parallel plates 30 and 36 of capacitor 32, conical emitter lens 38, converging lens 40, and window 42 are mounted in an elongate tubular housing 48 of a material such as stainless steel on a common axis 50 which is coincident with fuel pellet 12. window 42 is mounted in a ring 52 fixed to the flange end of tubular housing 48 and optical elements 38 and 40 are mounted in rings 54 and 56 received in the tubular housing. The parallel plate 30 of capacitor 32 is fixed to a ring 58 received in an annular carrier plate 60 mounted in tubular housing 48 and X-ray window 28 is mounted on a carrier ring 62 received in the housing. The optical components and carrier rings may be mounted on manipulator stages in order to facilitate alignment of the optical system.

Window 28 and plate 30 of capacitor 32 may be made of a beryllium foil having a thickness on the order of one to a few thousandths of an inch. Plate 36 of capacitor 32 may be a thin layer of a conductive material of the order of 1000 angstroms or more deposited directly on the face of conical emitter lens 38 and carrier plate 54. A high potential V may be applied to plate 30 of

capacitor 32 through ring 58 with carrier plate 60 being made of an insulating material and plate 36 being grounded through carrier ring 54. Alternatively, in order to decrease the voltage drop between capacitor plate 30 and tubular housing 48, thereby minimizing the chance of breakdown between the housing and the capacitor plate, both carrier rings 60 and 54 may be made of an insulating material and half of the total potential V of oppposite polarity may be applied to each plate 30 and 36. For example, a potential of $-V/2$ could be applied to plate 30 and a potential of $+V/2$ applied to plate 36.

Cathode 34, parallel plate capacitor 32 and Cherenkov emitter 38 operate in a highly evacuated chamber 66 defined by the cooperation of tubular housing 48, light window 42, and X-ray window 28. The various portions of chamber 66 are interconnected by passages 68 through carrier rings 54, 56, and 60. Beryllium X-ray window 28 separates chamber 66 of detector 10' from the less highly evacuated reactor chamber 24 (about 10^{-8} torr vs. 10^{-5} torr). Since beryllium window 28 must be made thin enough to permit X-ray emission from fuel pellet 12 to pass therethrough, it might rupture if chamber 24 were subjected to atmospheric pressure while chamber 66 was evacuated, such as when reactor chamber 24 is opened to the atmosphere. To prevent such rupture of window 28, a gate valve 70 with an atmospheric supporting plate 72 may be mounted on housing 48 between reactor chamber 24 and beryllium window 28. In the open position of valve 70, plate 72 is retracted so that X-rays can pass through window 28 and, in the closed position, plate 72 seals chamber 66 and beryllium window 28 from communication with reactor chamber 24, thereby preventing the window 28 from being subjected to the pressure within chamber 24. A bypass valve 74 enables both faces of window 28 to communicate with chamber 66 when gate valve 70 is closed, thereby preventing window 28 from being subjected to a pressure differential.

Chamber 66 is initially evacuated with gate valve 70 closed and bypass valve 74 open and, when fully evacuated, bypass valve 74 is closed. After chamber 24 has also been evacuated gate valve 70 is opened to permit X-rays emitted from fuel pellet 12 to pass through detector 10' and impinge on cathode emitter 34. When X-ray detector 10' is in operation bypass valve 74 will always be closed. Housing 48 of detector 10' may also have several ports therein (not shown) which are used for electrical feed throughs, vacuum pumping, alignment of optical elements, and adjustment of the distance between plates 30 and 36 of parallel plate capacitor 32.

As shown in FIG. 3, when an electron accelerated by capacitor 32 to a relativistic velocity passes into conical lens 38 through entrance end 76, light rays 78 are emitted by Cherenkov radiation in a cone with a half angle θ to the path of the electron which may be defined by the following expression:

$$\cos\theta = 1/\beta n \qquad (1)$$

where

$\beta = v/c$

n=the index of refraction of the transparent material,

v=the velocity of the electron in the transparent material, and

c=the speed of light in a vacuum. As shown in FIG. 4, the half angle ϕ of the conical exit surface 82 of lens 38 is chosen so that those light rays 78 which are emitted at an angle θ relative to the optical axis and in a plane defined by the axis of the conical lens and any radius vector of a cross section of the lens perpendicular to the optical axis will be refracted by exit surface 82 into parallel rays 84 of light. The half angle ϕ may be determined from the following relations obtained from FIG. 5:

$$\theta_i + \phi = \pi/2$$
$$\sin\theta_i = n \sin\theta_r$$
$$\sin\theta_r + \phi = \pi/2$$

from which the following is obtained:

$\theta_i = \theta + \theta_r$ and

$$\frac{\sin(\theta + \theta_r)}{\sin\theta_r} = \frac{\sin\theta\cos\theta_r + \cos\theta\sin\theta_r}{\sin\theta_r} = n,$$

from which may be obtained:

$$\tan\theta_r = \frac{\sin\theta}{n - \cos\theta} = \frac{1}{\tan(\theta + \phi)} \qquad (2)$$

From equation 2 the following expression for the half angle ϕ of the conical exit surface 82 of lens 38 may be derived:

$$\tan\phi = \frac{n\cos\theta - 1}{n\sin\theta}$$

For a conical lens 38 with an index of refraction n=1.335 bombarded by relativistic electrons with a velocity $\beta = 0.89$ the half angle θ at which Cherenkov radiation is emitted is 32.7° and the half angle ϕ is 9.73°. The frustoconical surface 86 of emitter lens 38 also has a half angle θ as shown in FIG. 4.

As shown in FIG. 6, since light produced by Cherenkov radiation is emitted in a cone of half angle θ, the locus of all points on the surface of entrance end 76 of the conical lens that emit rays which are refracted at a point P on conical surface 82 of the lens is the circular arc 88 which is the intersection of the surface of entrance end 76 with a right circular cone 90 of half angle θ with its vertex at point P. Only one point of this circular arc 88 will lie in a plane defined by the axis of the cone and point P; and thus, only a small portion ds of arc 88 will emit light that will emerge from point P as parallel rays 84 of light. Rays of light emitted on circular arc 88 from other than segment ds will emerge from conical surface 82 at point P in an angle greater than θ_i and will be directed as shown in FIG. 7 in an arc 92 which is concave toward the optical axis of lens 38.

As shown in FIG. 8, for any single point P on the conical surface 82 of lens 38, all of the emitted light, including the diverging rays, could be collected and converted into parallel rays of light by an ordinary convex lens 94 positioned so that its focal point is coincident with point P and the ray 84 parallel to the optic axis will pass through the center of the lens. Since the rays of light emerging from point P lie on a well-defined arc 92, it is only necessary to have a small segment of a lens to focus the light from point P and, therefore, entire lens 94 is unnecessary. This is true for any other point on a circle 97 of constant radius on the conical surface 82 of lens 38. Therefore, as shown in FIG. 9, collector lens 40 of device 10' has a plane surface 96 through which parallel rays 84 pass and a smooth surface 98 having the desired curvature to collect diverging light

rays from all of the segments of the arc 92 for each point P such that a larger fraction of the total light produced as Cherenkov radiation in lens 38 emerges from lens 40 in parallel rays 84 of light. Lens 40 may have a diameter many times larger than emitter lens 38 in order to efficiently collect the diverging light rays.

Conical emitter 38 and collector lens 40 will not convert all of the light emitted as Cherenkov radiation into parallel rays of light. Light emitted by electrons which have undergone scattering in the emitter will not be collected. Also, since the light emitted in lens 38 is not monochromatic, different wavelengths of the light will be emitted and refracted at slightly different angles and, thus, only light within a narrow range of wavelengths will be converted into parallel rays of light by emitter lens 38 and collector lens 40. Furthermore, since the emitted light emerges from a band rather than a circle on surface 82 of lens 38, only part of the skewed rays produced by undeflected electrons and within the range of wavelengths for which the lenses 38 and 40 were designed, will be converted into parallel rays of light. Nevertheless, by designing conical lens 38 to emit a parallel beam of light at the wavelength of maximum radiation intensity and designing collector lens 40 to provide maximum flux in the parallel beam, a reasonable fraction of the light emitted by Cherenkov radiation can be collected and focused with sufficient intensity on image converter camera 45. Light rays of other wavelengths which are not deflected into parallel rays by lenses 38 and 40 will be excluded either by entrance slit 44 or by pinhole spatial filter 43 together with entrance slit 44. It is believed the parameters discussed herein will enable persons skilled in the art to design satisfactory conical emitters 38 and collector lenses 40 for detectors 10'.

DETERMINATION OF RESPONSE TIME

The response time of detector 10' may be degraded by a number of different phenomena and, hence, the effect of these phenomena on the response time should be considered in designing an optimal detector having a desired response time for a particular portion of the X-ray spectrum of a fuel pellet under a particular set of conditions. The size of the area of cathode 34 that is bombarded by X-ray emission from fuel pellet 12 affects the response time of detector 10'. As shown in FIG. 10, if fuel pellet 12 is essentially a point source, the distance R_1 traveled by an X-ray from the fuel pellet to the center of cathode 32 is less than the distance R_2 traveled by an X-ray from the fuel pellet to the edge of cathode 34. This difference in path length, R_2-R_1 results in a difference in arrival times for X-rays emitted from fuel pellet 12 at the same instant of time which produces a degradation of the response time Δt equal to:

$$\Delta t=(R_2-R_1)/c \tag{4}$$

where c is the speed of light in a vacuum. If the distance R_1 from the fuel pellet 12 to the cathode 34 is known and it is required that Δt not exceed a maximum value δ, the maximum diameter d of the X-ray absorbing cathode 34 is:

$$d=2\sqrt{c^2\delta^2+2R_1c\delta}\simeq 2\sqrt{2R_1c\delta} \tag{5}$$

If $\delta=10^{-12}$ sec. and $R_1=50$ cm., then d=3.46 cm. This source of degradation is generally small compared with the degradation due to other phenomena.

Although liberation of electrons in cathode 34 by X-rays is essentially instantaneous relative to a picosecond, a finite time is required for liberated electrons to travel through and leave the thin layer of cathode material. Electrons liberated at the surface of the layer will begin to be accelerated sooner than electrons liberated from deeper inside the layer which must first escape from inside the layer before they can be accelerated. The degradation of the time response due to this effect should be less than one picosecond.

The time resolution of detector 10' is also degraded by the spread in the axial component of the initial velocity of the electrons ejected from cathode 34. The initial spread in the axial component of the electron velocity produces a spread in time of arrival of the electrons at the Cherenkov emitter lens 38 for electrons emitted at the same instant of time from cathode 34, thereby degrading the time resolution of the x-ray signal. This degradation is equal to the difference in transit time between parallel plates 30 and 36 of the parallel plate accelerator 32 for electrons emitted from cathode 34 with the highest initial axial velocity and zero initial axial velocity. In order to minimize this difference in transit time and, hence, the degradation in response time due to the spread in initial electron axial velocities, the electric field accelerating the electrons should be as large as possible.

The degradation of the response time due to the spread in initial electron axial velocities can be calculated from the relativistic equations of motion. The general relativistic formula for the acceleration a(t) of a particle of rest mass M_o and charge q in a uniform electric field E is given by

$$a(t)=\frac{qE}{M_o}\left[1-\frac{v(t)^2}{c^2}\right]^{3/2} \tag{6}$$

where v(t) is the particle velocity at time t and c is the speed of light in a vacuum. This equation can be integrated in the following way:

$$\int_{t=0}^{t=t}\frac{dv}{\left[1-\frac{v^2}{c^2}\right]^{3/2}}=\frac{qE}{M_o}t \tag{7}$$

where a (t)=dv/dt. Using the boundary conditions $v=v_o$ at t=0, the following expression for the transit time is obtained

$$t=\frac{M_o}{qE}\left[\frac{v}{\sqrt{1-\frac{v^2}{c^2}}}-\frac{v_o}{\sqrt{1-\frac{v_o^2}{c^2}}}\right] \tag{8}$$

where v is the axial component of the final velocity of the electron arriving at plate 36 and v_o is the axial component of the initial electron velocity at plate 30. The final velocity of the electron is given by the relativistic formula

$$v^2=c^2\left[1+\frac{M_oc^2}{E_k+M_oc^2}\right]\cdot\left[1-\frac{M_oc^2}{E_k+M_oc^2}\right] \tag{9}$$

where E_k is the kinetic energy of the accelerated electron upon leaving the electric field.

If the accelerating potential across plates 30 and 36 of accelerator 32 is 600 keV and the distance between the plates is 6.0 millimeters, the electric field will be 10^6 volts/cm, the final velocity attained by electrons with zero initial velocity will be $v=0.8879c$, and the electron transit time will be $t=32.93$ picosecond. If the greatest initial axial electron velocity is 5.9×10^9 cm/sec, corresponding to an initial kinetic energy of 10 keV, the kinetic energy of the electrons arriving at plate 36 would be 610 keV, their maximum attained velocity would be $v=0.890c$, and the electron transit time would be $t=29.86$ picoseconds. The degradation due to electron velocity spread would, therefore, be

$$t=3.07 \text{ picoseconds.}$$

Some electrons with initial kinetic energies greater than 10 keV can usually be expected for the X-ray spectrum produced by a laser irradiated fuel pellet 12, but these electrons are in most cases a negligibly small part of the total electron flux leaving cathode 34 and their effect on the response time should be undetectable. If all of the electrons have initial energies below 1 keV then acceleration by an electric field of 10^6 V/cm through a potential of 600 keV will result in a time degradation of less than 1 picosecond.

If a large fraction of the emitted electrons are produced as the result of secondary collisions of photoelectrons with other electrons in the cathode then most of the electrons leaving the cathode may only have initial kinetic energies of the order of 10 eV or less. Under these conditions for a potential drop of 600 keV a time resolution of 1 picosecond could be achieved with an electric field of only 10^5 V/cm. Since the accelerating potential must remain large in order to maximize the output of Cherenkov radiation, the smaller the accelerating electric field the greater the required distance between anode and cathode. If the interelectrode spacing becomes of the order of or greater than the anode and cathode diameters, then additional annular electrodes may be required between the cathode and anode to maintain a uniform accelerating electric field parallel to the detector axis. These electrodes would be similar to annular electrodes used in electron guns and electrostatic particle accelerators and methods for designing such electrodes are described in *Theory and Design of Electron Beams* by J. R. Pierce, Van Nostrand Publishing Co. (1954).

In order to reduce or eliminate the need for specially designed intermediate electrodes it is preferable to operate this detector at the highest permissible electric field, even if the electron velocities are sufficiently low that the spread in electron velocities is not the limiting factor in determining detector time response.

The time resolution of detector 10' is also degraded by its conical optical system which takes advantage of the conical nature of the wave fronts of the Cherenkov radiation to convert part of the emitted light into parallel rays. With conical optical elements the time response is degraded primarily because the Cherenkov radiation is emitted in lens 38 over a finite surface area. Consider two light rays emitted at the same angle at the same time and in the same plane, defined by the axis and a diameter d on the face 76 of the conical lens 38. As shown in FIG. 11, these rays will not be part of the same wave front because they have different optical path lengths. If the distance between the points at which the light is emitted is d, the difference in path lengths will be equal to:

$$d \sin \theta$$

where θ is the angle at which Cherenkov radiation is emitted in the medium and θ is defined by:

$$\cos \theta = 1/\beta n$$

where $\beta=v/c$ and n is the index of refraction of the emitter. The time degradation of the signal introduced by this effect is given by

$$\Delta t = dn/c \sin \theta. \tag{10}$$

For a given index of refraction n and a given β, Δt can be made arbitrarily small by limiting the dimensions of the entrance face of the emitter or by aperturing the X-ray signal so that the irradiated area of the cathode is limited. If the time response is to be degraded no more than 5 picoseconds due to this effect, then for $n=1.335$ and $\beta=0.89$ the maximum value for the diameter d of the exposed area on the entrance face 76 of conical emitter 40 is

$$d=2.08 \text{ mm.}$$

DESCRIPTION OF MULTIPLE SPOT INTENSITY DETECTOR

FIGS. 12 through 14 illustrate an X-ray detector 100 embodying this invention in which like reference numerals refer to the same components as those of detector 10'. Detector 100 has seven cathodes 34' each of which may be of a different thickness or material or both, thereby permitting detection of various segments of the spectrum of X-rays emitted from target 12 as a function of time. Alternatively, each cathode may consist of the same high-Z material and an array of X-ray attenuation filters of various materials would be positioned in front of the multiple cathodes in order to achieve selective spectral sensitivity. If parallel plate 30 of capacitor 32' is too large to easily be made of a single piece of thin foil supported in a ring, a self-supporting metal plate with a separate hole therein for each cathode 34' may be used in lieu of plate 30. A small piece of thin foil could overlie each hole and the surface of the whole plate with the foils fixed thereto would be polished to the desired surface finish. Then the desired X-ray absorbing material for each cathode 34' would be deposited on the thin foils.

For each cathode 34' detector 100 has a corresponding Cherenkov emitter conical lens 38' and collector lens 40' which produces seven separate beams of light with parallel rays leaving detector 100 through exit window 42. The beams of light pass through an array of pinhole spatial filters 43' and are focused into a row of spots 101 at the entrance slit 44 of an image converter camera 45 by an array of seven individually adjustable lenses 46' and seven individually adjustable mirrors 106. When the spots of light entering slit 44 are swept by the image converter camera 45, they produce a series of traces of light representing the intensity as a function of time of various segments of the spectrum of x-rays emitted by fuel pellet 12. The traces of light produced by image converter camera 45 may be amplified or increased in intensity by an image intensifier used in conjunction with such camera and be recorded on sensitive photographic film. When the exposed film is developed,

the density of the traces recorded on the film may be read on a microdensitometer.

With the same camera sweep time and time resolution, it is also possible to look at a longer interval of time of the x-ray spectrum by varying the path lengths of the different beams. As shown schematically in FIG. 15 for three light beams, the path length of each light beam may be varied by pairs of individually adjustable mirrors 108 located at different distances from mirrors 106. For example, with a suitable array of mirrors 106 and 108, seven identical cathodes 34', and a total camera sweep time of two nanoseconds, it is possible with detector 100 to look at a 14 nanosecond interval of x-ray emission with picosecond time resolution over the entire 14 nanosecond time interval of the x-ray emission.

DESCRIPTION OF IMAGING DETECTOR

FIG. 16 illustrates an x-ray detector 110 embodying this invention which produces time resolved images of fuel pellet 12 when it is emitting x-rays and in which like reference numerals refer to the same components as those of detector 10'. In detector 110 and X-ray image of fuel pellet 12 is produced at cathode 34 by a grazing incidence mirror system (not shown to scale) with a hyperbolic mirror 112, an ellipsoidal mirror 114, and a stop 116 shielding cathode 34 from direct bombardment by X-rays from fuel pellet 12. Such a grazing incidence mirror system is described by R. C. Chase and J. K. Silk in Applied Optics 14, 20 (1975). This X-ray image may also be produced by other means such as a pinhole aperture or a zone plate. The electrons emitted by cathode 34 are accelerated by parallel plate capacitor 32 and bombard a Cherenkov emitter in the form of a thin slab 118 of transparent material. A fraction of the light from thin slab emitter 118 is collected by a low f number double reflecting system of spherical mirrors 120 and 122 arranged and constructed similar to a Burch all-reflecting microscope objective. A lens system which may be corrected for chromatic aberrations is represented by lens 124 which adjusts the size and position of the image at the entrance slit 44 of an image converter camera 45.

Unlike detectors 10' and 100, the optical collecting and imaging system of detector 110 does not utilize or preserve the conical nature of the wavefronts in which light is emitted by Cherenkov radiation. Rather the optical system of detector 110 treats the light produced by Cherenkov radiation as if it were emitted and propagated in spherical wavefronts of light. Optical systems designed to propagate light in the form of spherical wavefronts are hereinafter referred to as spherical optical systems as opposed to conical optical systems designed to propagate light in the form of conical wavefronts which are hereinafter referred to as conical optical systems. While spherical optical systems cannot convert Cherenkov radiation into a parallel beam of light or focus it to a spot, they can be utilized to reconstruct an image from a source of Cherenkov radiation such as thin slab emitter 118.

As previously noted, the spread in the axial component of the initial velocity of the electrons emerging from cathode 34 degrades the response time of the detector devices. Similarly, the existence of a transverse or perpendicular component of the velocity of the electrons emerging from cathode 34 degrades the spatial or image resolution of detector 110. To improve the image resolution of detector 110, cathode 34 and electron capacitor accelerator 32 may be located inside a solenoid coil 126 which, when energized, decreases the smearing of the image caused by the transverse component of the velocity of the electrons. When energized, solenoid coil 126 produces a magnetic field parallel to the electric field or desired direction of axial acceleration of electrons between parallel plates 30 and 36 of accelerator 32.

This magnetic field decreases the transverse excursion of electrons emitted from cathode 34, thereby improving the spatial or image resolution of detector 110.

The angle θ at which light is emitted as Cherenkov radiation within thin slab emitter 118 must not exceed the critical angle θ_c for total reflection or the emitted light will not be able to pass through the exit face 128 of thin slab emitter 118. For light emerging into a vacuum the critical angle θ_c is given by:

$$\sin \theta_c = 1/n \tag{11}$$

where n is the index of refraction of thin slab emitter 118. The angle θ is a function of the relativistic velocity β of the electrons emitting the light as defined by equation 1. Therefore, with the thin slab emitter 118 the relativistic velocity of electrons impinging on the emitter must satisfy the requirement that:

$$\frac{1}{n^2} < \beta^2 < \frac{1}{n^2 - 1} \tag{12}$$

For example, if the index of refraction of thin slab emitter 118 is $n=1.5$ then the relativistic velocity of the electrons β may neither be less than 0.67 nor exceed 0.89.

Equation 12 imposes a restriction on β if $n^2-1>1$ or equivalently $n>\sqrt{2}$. If $n<\sqrt{2}$, the total internal reflection does not impose any restriction on β. For any given maximum operating voltage for the X-ray detector a value for the index of refraction can be found below which no upper limit will be placed on β within the range of operation of the detector. For example, if $V_{max}=600$ keV, then $n=1.5$ imposes no operational restriction due to total internal reflection, since no attainable values of β exceed 0.89.

The maximum diameter of thin slab 118 of detector 110 is not limited for a given time resolution by equation 10 and is subject only to the much less stringent requirements of equation 5. This is because when a spherical collecting and imaging optical system is used, the rays from all points on the face of the emitter are not superimposed in a focused spot, but are imaged so that rays emitted from different points on the face of the emitter are imaged at corresponding points in the image plane. Becuase the diameter of the detector is not limited by equation 10, the total amount of light produced by a thin slab emitter and spherical optical collecting system can be much greaater than for a conical emitter with the same time resolution for the same intensity of X-rays at cathode 34.

The reconstruction of conical wavefronts produced by Cherenkov emission into a series of spherical wavefronts by a spherical optical collecting and imaging system does, however, cause an inherent degradation of the response time which is independent of the diameter of thin slab emitter 118. The time required for an electron to move a distance l_1 through a material with an index of refraction n at a constant velocity β is $\Delta t = l_1/\beta c$. During this same time Δt a conical wavefront starting from the same point as the electron will

propagate a distance $l_2=(c/n)\Delta t$ at an angle θ relative to the trajectory of the electron. At the end of the time interval Δt the conical wavefront of Cherenkov radiation produced by the electron can be approximated by a band of spherical wavefronts of thickness

$$\delta=l_1-l_2\cos\theta \quad (13)$$

which produces a smearing of the signal in time of $\Delta\tau=n\delta/c$.

The electrons do not, however, travel at a constant velocity, but slow down as they progress into the medium. This will reduce the width of the band of spherical wavefronts produced by the radiation. Also, most of the electrons will undergo scattering along their path length. Conical optical systems reject most of the light emitted by electrons which have slowed down or undergone large angle collisions, but low f number spherical optical systems will collect and image a large fraction of this light. An upper limit on the time degradation produced using a thin slab emitter with a spherical optical collecting system can be obtained by assuming the photons which are collected are emitted at all angles up to θ_c where $\sin\theta_c=1/n$.

An undeflected electron which enters the emitter with an initial energy E_{max} and slows down to an energy E in the emitter traverses a distance y given by

$$y(E)=16.79/D(E_{max}^{1.46}-E^{1.46}) \quad (14)$$

where D is the material density in mg/cm^3 and y is in cm when the energies E_{max} and E are given in hundreds of keV. Equation 14 is derived using the range equation 26 set forth hereinafter. The time required to travel this distance can be obtained from

$$t=\int_0^y dl/\beta c \quad (15)$$

An electron with an initial velocity $\beta=0.89$ entering an emitter with an index of refraction n=1.5 emits Cherenkov radiation until it slows down to a velocity $\beta=0.67$. If the density of the medium $D=2200\ mg/cm^3$ the distance traveled by the electron in slowing down will be 0.089 cm from equation 14. The time required for the electron to traverse this distance will be 3.7 psec. A ray of light produced at $t=0$ will travel 0.075 cm in this same time interval. The degradation of the time resolution of the image resulting from the use of a spherical optical collecting system will, therefore, be

$$\Delta\tau=1.7\ psec$$

from equation 13.

This is an upper limit on the inherent time degradation resulting from using a spherical optical system to collect light from a slab Cherenkov emitter. In general, light emitted at angles close to θ_c relative to the optic axis will not be collected because the light rays emerging from the thin slab will miss the collecting mirror 120. Light emitted at small angles relative to the optic axis will be blocked by the back side of mirror 122. Also, most of the electrons will not penetrate the maximum undeflected distance into the emitter while emitting Cherenkov radiation and more radiation will be emitted at the beginning of the electron trajectory when β is greatest. All of these factors tend to reduce the inherent time degradation of the detector. The actual degradation of the time response of detector 110 resulting from the reconstruction of Cherenkov emission into spherical wavefronts of light should, therefore, be less than 1 psec.

The light emitted by thin slab emitter 118 may be imaged onto the entrance slit 44 of image converter camera 45 to produce a time resolved streak of a thin slice of the target image. Detector 110 may also be used to take "snapshots" of the implosion phase of fuel pellet 12 if used in conjunction with an electro-optical Kerr cell interposed between a pair of polarizers and controlled by a laser pulse, so that the Kerr cell functions as a shutter controlling the admission of light to a camera with sensitive photographic film. The Kerr cell provides an extremely fast shutter which can be opened for a few picoseconds at a time to permit the photographic film to record images of picosecond segments of the implosion phase of the fuel pellet which would enable detection of instabilities which may develop in the fuel pellet during the implosion phase of the laser fusion process.

Because the contrast ratio of an optically triggered Kerr cell shutter is only about a factor of 1000, light detected during the time the shutter is closed may produce background noise which may reduce the resolution of the snapshot image. If this becomes a problem a fast framing camera may be used to reduce the time interval over which the camera is capable of accepting light but the optical Kerr cell shutter is off.

The light passing through the Kerr cell shutter will be intensified by an image intensifier before being recorded on photographic film. Scattered laser light from the laser pulse triggering the Kerr cell shutter may be prevented from entering the image intensifier by a filter which transmits the light from detector 100 but is opaque at the frequency of the laser light. If the light from detector 110 is of sufficient intensity, a series of picosecond snapshots of the fuel pellet may be taken at different times by using a Kerr cell shutter in conjunction with multibeam optical sampling techniques similar to those described by Vogel, Savage, and Dugay in IEEE Journal of Quantum Electronics 10, 642 (1974). If a series of snapshots is taken, background noise may be subtracted from the images using known computer image enhancement techniques.

Optically triggered Kerr cell shutters will remain open for only a few picoseconds to a few tens of picoseconds. An image converter camera with an image intensifier will be gated on for about one nanosecond at its fastest framing speed and will produce a trace during approximately a two nanosecond interval of time at its fastest sweep speed. Therefore, when cameras with Kerr cell shutters and image converter cameras are utilized in conjunction with X-ray detectors embodying this invention, they must be triggered at precisely the right time in order to record the desired event. If an X-ray detector embodying this invention is utilized with an image converter camera to record an event in a laser driven fusion process, the image converter camera can be triggered by a sub nanosecond electrical signal provided by a fast photo diode monitoring the laser beam irradiating the fuel target. If an X-ray detector embodying this invention is utilized in conjunction with a Kerr cell shutter, the Kerr cell may be optically triggered by a laser pulse picked off from the source of the laser beam irradiating the target by a beam splitter and, if necessary, amplified to actuate the Kerr call. The pulse

triggering the Kerr cell can be synchronized relative to the arrival of the laser beam at the target to within better than a few tens of picoseconds by the two photon fluorescence technique.

In addition to synchronization of the laser pulse for triggering a Kerr cell shutter, the pulse must also be of the correct duration in time. Pulses with the necessary picosecond duration for correctly triggering a Kerr cell shutter can be obtained from a mode locked laser oscillator. The mode locked laser oscillator will produce a train of pulses from which a single pulse may be picked off by a pair of Pockles cells. The single pulse may be divided by a beam splitter with one portion being used to irradiate the fuel target and the other portion being amplified and used to trigger the Kerr cell. The portion of the divided pulse used to irradiate the target may be shaped by a device such as a pulse stacker and then amplified to provide a laser pulse having the necessary duration and intensity configuration for proper radiation of the fuel target.

The minimum duration of the divided portion of the pulse for triggering the Kerr cell is dependent on the band width of the light of the divided pulse. Trigger pulses containing a very narrow spread of frequencies have longer durations that trigger pulses containing a broad band of frequencies. In accordance with the Heisenberg uncertainty principle, the minimum duration in time Δt of a mode locked laser trigger pulse with a spread in energies ΔE of the spectral components of the band width is given by:

$$\Delta E \cdot \Delta t > h \tag{16}$$

where:

h is Planck's constant.

The mode locked pulse from a source such as a YAG laser oscillator is typically on the order of 30 picoseconds full width at half the maximum amplitude of the intensity of the pulse (FWHM). This mode locked pulse may be adquate for triggering a Kerr cell shutter under some conditions when an extremely fast time resolution is not required. To obtain a laser trigger pulse of shorter duration an oscillator producing laser pulses with a larger spread of frequencies must be used. For example, an oscillator with a neodymium doped glass rod will produce a mode locked pulse with a sufficient spread of frequencies of laser light to have a duration of about one picosecond which may be utilized to trigger a Kerr cell shutter. However, this pulse may be of too short a duration for use in a pulse shaping network such as a pulse stacker for producing a laser beam for irradiating the target. Therefore, after using a beam splitter to pick off a suitable portion of a mode locked pulse of short duration for triggering the Kerr cell, the remaining portion of the pulse may be passed through an etalon filter to decrease its spread of frequencies and thereby sufficiently increase its duration so that it may be utilized by the pulse shaping network to produce a laser beam of the desired duration and intensity distribution for irradiating the fuel target.

Detector **110** can be modified to operate like a single spot detector by removing the grazing incidence mirror system to expose the cathode **34** directly to X-rays from the target rather than producing an X-ray image at the cathode and by modifying lens system **124** to produce a reduced image at the entrance slit **44** of image converter camera **45** which is so small that it approximates a spot. This modification of detector **110** can be used to obtain time resolved spectral information from the X-rays by depositing a number of different K edge materials on different areas of cathode **34**. A time resolved snapshot of the emitter using a Kerr cell shutter will show different regions of the cathode radiating at different intensities. If the different K edge materials are deposited on the cathode as a series of parallel strips and the Cherenkov signal is focused onto the entrance slit of an image converter camera, then the regions with different cathode materials will produce traces of different intensity as a function of time. This information can be used to determine the shape of the X-ray continuum spectrum produced by the target. Alternatively instead of coating cathode **34** with different K edge materials, the cathode can be coated with a single X-ray absorbing material such as gold and strips of different K edge materials can be placed in front of window **28** so that the X-rays entering the detector have been spectrally filtered before they arrive at cathode **34**.

DETERMINATION OF IMAGE RESOLUTION

Without the magnetic field produced by solenoid coil **126** electrons emitted from a point on cathode **34** of detector **110** with a maximum spread in transverse velocities of 1.9×10^9 centimeters per second, which corresponds to a spread in initial transverse kinetic energies of 1 keV, would degrade image resolution by producing on entrance surface **76** of conical lens **38** of detector **110** a spot, not a point, with a radius of $6.3\ 10^{-2}$ centimeters, assuming plates **30** and **36** of the electron accelerator are spaced apart 6 millimeters and an electric field of 10^6 volts/centimeter. However, if solenoid coil **126** is energized, the magnetic field B produced thereby would reduce the radius r of this spot to:

$$r=2mv/qB=1.16\times10^{-10}\,v/B \tag{17}$$

where:

r is in centimeters

v is in centimeters per second, and

B is in kilogauss.

For a transverse velocity of 1.9×10^9 centimeters per second and a magnetic field of 30 kilogauss produced by solenoid coil **126** the radius of this spot would be reduced to 73 microns. Since the distance an electron travels transverse to optical axis **50** of detector **126** is independent of the image size, increasing the size of the image at the cathode decreases the relative image degradation. For a magnification at cathode **34** of 50x the degradation in image resolution produced by a spot with a radius of 73 microns is less than the degradation of the image inherently produced by the x-ray imaging means whether it be a grazing incidence mirror, a pinhole, or a zone plate. Therefore, solenoid coil **126** may be utilized to effectively decrease degradation of the image by transverse component of the velocity of the electrons emitted from cathode **34** of detector **110** to less than the degradation of the image inherently produced by the x-ray imaging means.

If most of the electrons emitted by cathode **34** have energies of the order of 10 eV or below, then the maximum detectable spread in velocity may be less than a tenth of that calculated above. Without a magnetic field the maximum sized spot produced would have a radius of only 63 μm for the detector parameters given above, and with a 30 kg magnetic field a spot of radius 7.3 μm would be produced at the entrance face of emitter **118** by the electrons emitted from a point on the surface of

cathode 34. This means that if most of the emitted electrons have energies below 10 eV it would be possible to use lower magnification or lower magnetic field strength without reducing the image resolution below that of the x-ray imaging device which produced a focused image of the target at cathode 34.

OTHER FORMS OF CHERENKOV EMITTERS AND OPTICAL SYSTEMS

X-ray detectors embodying this invention which focus the emitted Cherenkov radiation to a spot as in detectors 10' and 100 could utilize conical prisms as Cherenkov emitters rather than conical lenses 38. As shown in FIG. 17, a conical emitting prism 134 will produce parallel rays 136 of emerging light by total internal reflection rather than refraction. If the half angle ϕ' of conical prism 134 is equal to $\theta/2$, light rays, emitted at angle θ in a plane defined by the axis of the conical prism and any radius vector perpendicular to the axis and reflected at a point P in such a plane, will leave the prism parallel to the optical axis. As shown in FIG. 18, light rays 138 reflected at point P which were not emitted in such plane diverge from reflecting point P in an arc 140 which bends away from rather than toward the axis. Consequently, the curvature 142 of a suitable collector lens 144 (FIG. 19) for conical prism emitter 134 is determined by the locus of all simple lens segments which convert the diverging non-parallel rays emitted at each point P on a circle 145 into parallel rays of light 148. Thus, the collector lens 144 used with a conical emitting prism will be similar in shape to the collector lens 40 used with conical emitter 38. The degradation of response time produced by conical prism emitters may be determined from equation 10. Lens 144 may have a diameter many times larger than emitter 134 in order to efficiently collect the diverging rays of light.

As shown in FIG. 20, in spot detectors the Cherenkov radiation can be emitted and collected in conical wavefronts by a thin slab conical frustum emitter 150 and a system of conical mirrors. If the index of refraction n of thin slab emitter 150 is greater than $\sqrt{2}$, equation 12 restricts the maximum permissible electron velocity β in the same way as a thin slab emitter used with a spherical optical system. The light from thin slab emitter 150 is collected by conical mirrors 152 and 154 which are arranged and designed to reflect into parallel rays light emitted in slab 150 at an angle θ relative to the optical axis and in a plane defined by the optical axis of the slab and a radius vector perpendicular to the axis of the slab. If the half angle of mirror 152 is ϕ and the light rays emerge from the exit face 156 of the slab at an angle θ_L corresponding to Cherenkov emission at angle θ, the light emitted in such plane will be reflected into parallel rays if the half angle of conical mirror 154 is equal to $\phi-\theta_L/2$. Light rays 158 emitted at an angle θ relative to the optical axis but not emitted in these planes will be reflected in off-axis conical arcs as in the case of conical lenses 38 and conical emitter prism 134. A fraction of these off-axis rays 158 may be converted into parallel rays 160 by a collector lens 162. The curvature of optical surface 164 of lens 162 is determined by the locus of all simple lens segments which convert the off-axis rays into parallel rays as in the case for lenses 40 and 144 and has a similar shape. The rays of light emerging from collector lens 162 may be spatially filtered by a pinhole filter 43 and focused to a spot at the entrance slit 44 of an image converter camera 45 by a simple lens system 46.

As shown in FIG. 21, a fiber optic plate 186 may be used as a Cherenkov emitter with a spherical optic collecting system in imaging detectors embodying this invention. The light transmitted from fiber optic plate 186 can be collected by spherical mirrors 120 and 122 and focused by a lens system 124 onto the entrance slit 44 of an image converter camera 45. Fiber optic plate 186 may produce a sharper image than that produced by thin slab conical frustum 150 because the object plane is well defined at the exit face of plate 186.

Plate 186 has an array of a plurality of transparent fibers 188 with a higher index of refraction n_1 embedded in an opaque cladding 190 with a lower index of refraction n_2 so that the side wall 191 of each fiber is engaged by the cladding and the entrance and exit faces 192 and 194 of each fiber are exposed. Since light is transmitted through fibers 188 of plate 186 by total internal reflection, there is a maximum half angle θ_m for Cherenkov emission of light by undeflected electrons which must not be exceeded if the light is to be transmitted through the fibers of the fiber optic plate 186. It will be apparent from FIG. 22 that for an undeflected electron the maximum half angle θ_m of a cone of light which will be transmitted through the fibers 188 of plate 186 is:

$$\theta_m=\pi/2-\theta_c \tag{18}$$

where:

θ_c is the minimum angle of incidence for total internal reflection of light along the fiber.

The minimum angle θ_c for total internal reflection is given by:

$$\sin\theta_c=n_2/n_1 \tag{19}$$

where:

n_1 is the index of refraction of the fiber, and

n_2 is the index of refraction of the cladding.

As previously indicated, equation 1 defines the cone half angle θ at which light is emitted as Cherenkov radiation as a function of the velocity of the electrons in fibers 188 and the index of refraction thereof as follows:

$$\cos\theta=1/n_1\beta$$

Thus, substituting equations 19 and 1 into equation 18 defines the maximum permissible velocity β of an undeflected electron which will result in transmission in fibers 188 by total internal reflection by side walls 191 of the light emitted therein by the electron as:

$$\beta<1/n_2 \tag{20}$$

For internally reflected light to be transmitted through exit face 194 of fibers 188 the velocity β of the electron must also comply with the restriction of equation 12 that:

$$\frac{1}{n_1^2}<\beta^2<\frac{1}{n_1^2-1}$$

Therefore, if

$$n_1^2<n_2^2+1 \tag{21}$$

equation (20) will determine the upper limit of the electron velocity in fibers 188 of plate 186 for which Cherenkov radiation can be transmitted; and if

$$n_1^2 > n_2^2 + 1 \quad (22)$$

equation 12 will determine the upper limit of the electron velocity in the fibers of the plate. For example, if $n_1=1.5$ and $n_2=1.3$, the electron velocity β is limited by equation 20 and may not exceed 0.769; and if $n_1=1.7$ and $n_2=1.3$, equation 12 will determine the upper limit of the electron velocity β which may not exceed 0.727.

The degradation of the time resolution due to reconstruction of conical wavefronts into spherical wavefronts is the same as for a thin slab emitter if relation 22 holds. If relation 21 holds then

$$\delta = l_1 - l_2 \sin\theta_c = l_1 - l_2 n_2/n_1$$

where l_1 and l_2 are defind as in equation 13 and the degradation in the time response is given by $\Delta\tau=n_1\delta/c$. For example, if $n_1=1.5$, $n_2=1.3$, the density of emitter material n_1 is 2200 mg/cm^3 and the initial electron velocity $\beta=0.769$, then $l_1=0.0182$ cm, $l_2=0.0174$ cm and

$$\Delta\tau=0.16 \text{ psec}$$

compared with a time degradation of 1.7 psec for a thin slab emitter with index of refraction n_1. The reduction in time degradation is achieved at the expense of intensity since the maximum permissible electron velocity is reduced.

The various systems described herein may be refined and optimized by the use of known three dimensional ray tracing and computer optimization techniques. The optical systems utilized in detector devices embodying this invention should be corrected by known techniques for the most detrimental of the various aberrations such as chromatic aberrations, spherical aberration, coma, astigmatism, curvature of field, and distortion. The optical collecting systems may be corrected for chromatic aberration over a range of frequencies by known optical design techniques so that a larger fraction of the light emitted by Cherenkov radiation can be focused onto the entrance slit 44 of image converter camera 45. For optimum detector performance, the optical system as a whole must be designed to reduce chromatic aberration and produce maximum intensity. This requires the use of three dimensional computer ray tracing techniques. Computer programs employing these techniques are commercially available and can be used to optimize the design of the optical system.

MATERIALS FOR EMITTERS AND OPTICAL COMPONENTS

As will be shown, restrictions imposed by time resolution in conical emitters, total internal reflection for thin slabs and fiber optics plates, and light losses to the cladding in fiber optic plates limit the choice of materials that can be used to obtain efficient production and collection of Cherenkov radiation in the x-ray detectors described in this disclosure. Because the intensity of Cherenkov radiation increases as the wavelength of the emitted light decreases, materials used for the emitter and transparent elements of the optical system should be good transmitters of soft ultraviolet radiation. Some of the materials which satisfy this requirement are the fluorides, NaF, LiF, CaF_2, and MgF_2, and fused silica glass.

For conical emitters there is a range of indices of refraction between 1.3 and 1.5 for which emission of Cherenkov radiation will be maximuzed for the electron energies typically generated in this device. The collectable Cherenkov emission is also dependent on the undeflected path length of electrons in the material. The range of electrons in a material is approximately inversely proportional to material density and undeflected range increases as the atomic number of the emitting material decreases. Therefore, some low density, low atomic number materials may be superior materials for conical emitters even if their indices of refraction are outside the optimum range.

In spherical optical systems degradation of the time resolution does not restrict the index of refraction of the emitting material for time resolution on the order of 1 psec or greater. However, the value of the index of refraction of the emitter material may place a restriction on the maximum value for β for a given configuration. For example, for thin slab emitter 150, if $n>\sqrt{2}$ then β is limited by equation 12. For a given maximum value of β, the emitter material should be chosen with as high an index of refraction as possible consistent with efficient collection of the emitted light by a low f number optical system. Materials such as CaF_2 and fused silica are believed to be good choices for thin slab emitters for spherical optical systems.

If a fiber optic plate is used as an emitter, it may be necessary to specially fabricate the plate in order to obtain the desired indices of refraction for both the fibers and the cladding. Commercially available fiber optic plates generally have high indices of refraction for the fibers, which limit the permissible value of β, or relatively small differences between the index of refraction of the fibers and the cladding which also limit the permissible value of β. However, ultraviolet transmitting fiber optic plates with fused silica fibers with an index of refraction of about 1.5 have recently been developed and are believed to be suitable for use in detectors embodying this invention. The material used for the cladding in any fiber optic plate should if possible be optically absorbing in the spectral region over which Cherenkov radiation is collected by the optic system and have as low an index of refraction as possible. If the emitter is supported in a cryogenically cooled mount, it is believed a fiber optic plate with fused silica fibers and cladding of solid water (H_2O) could be used. To make the cladding of water opaque, a light absorbing dye could be dissolved in the water. For a fiber optic emitter with fused silica fibers ($n_1\sim1.5$) and a cladding of solid cryogenically cooled H_2O ($n_2\sim1.22$) the value of β will be restricted to not more than 0.82.

Since the intensity of Cherenkov radiation increases with decreasing wavelength of the emitted light, the emitters and optical systems of the detectors could be designed to optimize the emission and collection of Cherenkov radiation in the ultraviolet portion of the spectrum. If the emitter and all lenses and windows used in the optical system are made of ultraviolet transmitting materials, the detector can then be optimized to produce shorter wavelength radiation in the ultraviolet and near ultraviolet portions of the spectrum. An optical system designed to detect vacuum ultraviolet radiation must be completely contained in a vacuum system. If the fast optical detector is an image converter camera, the phototube of the camera would be sealed to the vacuum system containing the optical system. The phototube would also be specially designed with an entrance window which transmits ultraviolet radiation

and a photocathode which is chosen to have a high sensitivity to ultraviolet radiation in the spectral region that the optical system is designed to transmit. Several materials are known which transmit ultraviolet radiation and can be used to fabricate optical elements. Some of these are NaF, LiF, CaF_2, MgF, fused silica, and crystal quartz.

Although the total quantity of light from the detector can be increased by optimizing the optical system to detect radiation in the ultraviolet and near ultraviolet region of the spectrum, there are factors which reduce the benefits to be obtained from so doing. The indices of refraction of all emitter materials increase with decreasing wavelength of the emitted light. This means that the diameter of the face of a conical emitter lens must be somewhat smaller for an optical system which is designed to transmit ultraviolet radiation than for an optical system which is designed to operate at visible wavelengths. Dispersion also increases as wavelength decreases and the band of frequencies which can be effectively corrected for chromatic aberration may be narrower in the ultraviolet region of the spectrum than at visible wavelengths.

RADIANT FLUX AND INTENSITY OF LIGHT

The radiant flux and intensity of the light produced by the x-ray detectors must be sufficient to be detected by the photodetector which may be an image converter camera **45**. In general, the intensity of this light is dependent on the quantity and spectral distribution of the x-rays from fuel pellet **12** impinging on the cathode of the detector, the quantity of the electrons emitted by the cathode, and the efficiency of the optical system in collecting and focusing the light from the Cherenkov emitter.

The quantity of electrons produced by cathode **34** may be maximized for a given spectral distribution of x-rays emitted from fuel pellet **12** by selectrion of an appropriate material for the cathode and the thickness of the cathode. The appropriate material and thickness can be determined from the well-known relations for x-ray absorption as a function of x-ray energy and atomic number of the absorber material, from the relationships for electron range in different materials as a function of electron energy, and from the relations for the production and escape of electrons from a surface of a material as a result of bombardment of the material by x-rays (for example, see G. F. Dionne, Effects of Secondary Electrons Scattering on Secondary Emission Yield Curves, Journal Applied Physics Vo. 44, No. 12, page 5361, December 1973). Using these relations, calculations may be made by known computer optimization techniques to determine the optimum material and cathode thickness for a given x-ray spectral distribution. Typical thickness for cathode **34** is on the order of a few thousand angstroms or less and typical optimized conversion efficiencies are on the order of one to ten percent depending on the spectrum of x-rays incident on the cathode.

For a given flux of electrons from cathode **34** the maximum number of photons of light produced by Cherenkov radiation will be dependent on the velocity of the electrons, the index of refraction of the emitter, and the area bombarded by electrons at the entrance end of the emitter. The theory of Cherenkov radiation by Frank and Tam as set forth in *Nuclear Physics* by W. E. Burcham, McGraw Hill Publishing Co., 1965, at pages 159–161 shows that the rate of energy lost by a single charged particle due to Cherenkov radiation is given in cgs units by:

$$\frac{dE}{dx} = \frac{4\pi^2 z^2 e^2}{c^2}\left(1 - \frac{1}{\beta^2 n^2}\right)\nu d\nu \tag{24}$$

where:

E=the energy radiated by Cherenkov emission

z=the number of charge units of the moving particle, which is 1 for an electron

e=the magnitude of the charge of the particle which for an electron is 4.8×10^{10} statcoulombs,

ν=the frequency of the radiation.

Equation 24 defines the energy loss due to Cherenkov emission of a charged particle such as an electron for all frequencies at which Cherenkov radiation is emitted by the particle. However, only a limited range of frequencies of the emitted light will actually be collected by the optical system. The intensity of emitted Cherenkov radiation increases with decreasing optical wavelengths, but ultraviolet radiation may be reabsorbed in the emitting material and, therefore, it is not collected. The intensity of emitted Cherenkov radiation, therefore, peaks in the blue or near ultraviolet portion of the spectrum depending on the emitting material used. Furthermore, the optical collecting system can only be designed to collect light from the emitter in a limited range of frequencies usually chosen near the frequency of peak intensity of the light leaving the emitter. Even if the optical system is corrected for chromatic aberration, it still is only corrected for a finite range of frequencies, say between the frequencies of red and blue light.

The number of photons of light produced in the emitter per electron can be calculated by integrating equation 24 over the range of wavelengths from λ_1 to λ_2 in which Cherenkov radiation is expected to be detected, where wavelength refers to the vacuum wavelength for a given frequency of light. For photon wavelengths between λ_1 and $\lambda_2[\lambda_2>\lambda_1]$ the number of photons of light N produced by a single electron traveling a distance l at a velocity β in a medium with an index of refraction n is given by:

$$N = \frac{4\pi e^2}{hc} l\left[1 - \frac{1}{\beta^2 n^2}\right]\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right] \tag{25}$$

where Planck's constant h is 6.63×10^{-27} erg seconds. For example, an electron moving at a constant velocity $\beta=0.89$ in a transparent emitter medium with an index of refraction n=1.335 would produce by Cherenkov radiation about 17.8 photons of light per millimeter with vacuum wavelengths in the range between 3,000 to 5,000 angstroms.

The path length l of an undeflected electron in an emitter during the time the electron emits Cherenkov radiation may be determined from the difference between the maximum undeflected electron range and the undeflected electron range at which the electron stops emitting Cherenkov radiation. The maximum undeflected range as a function of the kinetic energy E_k of electrons in materials has been measured and to a good approximation is independent of the particular material through which the electron passes when the ranges are expressed in mg/cm^2. An approximate formula for the maximum undeflected range R of an electron as a function of the kinetic energy E_k of an electron is:

$R = 16.79E_k^{1.46}$

where R is in mg/cm^2 and E_k is in hundreds of keV. From equation 9 an expression of the kinetic energy E_k of the accelerated electron as a function of its velocity β may be derived as:

$$\beta^2 = 1 - \left(\frac{E_o}{E_k + E_o}\right)^2 \quad (27)$$

where E_o is the rest mass of the electron which is 511 keV.

Utilizing equations 26 and 27 and knowing the density of the transparent material through which the electron passes, the undeflected path length l may be calculated. For example, if NaF with an index of refraction of n~1.335 in the spectral region of interest and a density of 2.558 g/cm^3 is chosen as the emitter, then Cherenkov radiation will be emitted for values of β of 0.75 and above. If the velocity β of an electron upon entering into and moving through the emitter is reduced from $\beta=0.89$ to $\beta=0.75$, then the undeflected path length l of the electrons will be 167 mg/cm^3 which for NaF is 0.65 mm. However, most of the electrons will not traverse the entire path length l without being deflected by large angle scattering. The lower the atomic number Z of the transparent material the longer the mean free path length l_m before large angle scattering takes place. Thus, the lower the atomic number of the emitter material the larger the fraction of emitted photons of light which exit from the emitter for collection and focusing by the optical system. This effect is greater for conical collecting systems than for spherical collecting systems, because conical systems reject most of the light produced by electrons which have slowed down or undergone large angle collisions while spherical systems collect a large fraction of this light. It is, therefore, reasonable to expect that spherical optical systems would be at least an order of magnitude more efficient in collecting emitted light than conical optical systems.

An expression for the total number of photons of light N produced by Cherenkov radiation in a given frequency range can be derived from equations 24, 26, and 27. From equation 24 the differential of the number of photons of light per electron dN may be expressed as:

$$dN = \frac{4\pi^2 e^2}{hc^2}\left(1 - \frac{1}{\beta^2 n^2}\right) d\nu\, dx, \quad (28)$$

and from equation 26 an expression for dx as a function of the range R of undeflected electrons and the density D of the emitting material in mg/cm^3 may be derived as:

$$x = \frac{R}{D} = 16.79\frac{E^{1.46}}{D} \quad (29)$$

$$dx = 24.5\frac{E^{0.46}}{D}\, dE$$

If equations 27 and 29 are substituted into equation 28, the number of photons N emitted per electron in a given frequency range $d\nu$ can be expressed as:

$$N = \frac{98\pi^2 e^2}{hc^2 D}\left[\int\left(1 - \frac{1}{n(\nu)^2\left[1 - \left(\frac{5.11}{5.11 + E_k}\right)^2\right]}\right) E_k^{0.46}\, dE_k\right] d\nu \quad (30)$$

The integration over the variable E_k of equation 30 goes from the kinetic energy of the electron upon initially entering the emitting material to the kinetic energy at which the electron ceases emitting Cherenkov radiation for which $\beta = 1/n$. From equation 27 this lower energy level at which the electron ceases emitting Cherenkov radiation is:

$$E_k = \left(\frac{n}{\sqrt{n^2 - 1}} - 1\right) 5.11 \quad (31)$$

where E_k is in hundreds of keV's. To obtain the total number of photons of light emitted by Cherenkov radiation in the frequency range which can be detected by a photodetector such as image converter camera 45 after the light has passed through the optical system, equation 30 must be integrated over such a range of frequencies. In equation 30 the index of refraction of the emitter material is not assumed to be constant but may vary with the frequency of the light emitted therein by Cherenkov radiation. It the emitter material is NaF with a density of 2.558 g/cm^3 and the average value of the index of refraction [N=1.335] is used in the integral, then the solution of equation 30 indicates that 6.8 photons of light per electron will be emitted in the range of 3,000 to 5,000 angstroms for an electron with an initial velocity $\beta=0.89$. If the emitter material is fused silica with an average index of refraction of 1.45 and a density of 2.20 g/cm^3, then the solution of equation 30 indicates that 16.2 photons of light per electron will be emitted in the range of 3,000 to 5,000 angstroms for an electron with an initial velocity of $\beta=0.89$.

The efficiency of the optical system in collecting and focusing the light from the emitter will be primarily dependent on the particular design thereof and may range from less than 1 percent to more than 10 percent. The range of wavelengths of light collected by the optical system will affect the intensity of the light received by the photodetector such as image converter camera 45. For a conical optical system which has not been corrected for chromatic aberrations, the wavelengths collected will lie in a narrow band around the wavelength of peak intensity of the emitted light. If a conical system is corrected for chromatic aberrations using known optical design techniques or if a spherical optical collecting system is used which has been corrected for chromatic aberrations, the range of frequencies collected will be greater, and hence, the amount of light collected will be greater.

Considering only those parameters of equation 30 which can be varied in constructing an x-ray detector, the number of photons of light N produced in an emitter for a given flux of electrons and a given initial value of β is proportional to:

$$N \propto \frac{d^2}{D}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\int\left(1-\frac{1}{n^2\beta(E_k)^2}\right)E_k^{0.46}\,dE_k \quad (32)$$

where d is the diameter of the face of the emitter and n is assumed to be constant having a value equal to the average value of n in the interval $\lambda_2-\lambda_1$. The integration is performed from the electron kinetic energy for which $\beta=1/n$ given by equation 31 to the initial energy with which electrons enter the emitting material.

By using equation 1, which defines the angle at which light is emitted by Cherenkov radiation, to rewrite equation 10, which defines the time degradation produced by a conical optical system; the diameter d of the entrance face of the conical emitter may be defined as:

$$d=\frac{c}{n}\Delta t\left(1-\frac{1}{\beta_{max}^2 n^2}\right)^{-\frac{1}{2}} \quad (33)$$

which when substituted into relation 32 gives:

$$N \propto \frac{1}{D}\left(\frac{c\Delta t}{n}\right)^2\left[1-\frac{1}{n^2\beta_{max}^2}\right]^{-1}\left[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right]\int\left(1-\frac{1}{n^2\beta(E_k)^2}\right)E_k^{0.46}dE_k \quad (34)$$

$$\propto \frac{c^2\Delta t^2}{D}\left[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right]Q$$

The quantity Q, defined by

$$Q=\frac{1}{n^2}\left[1-\frac{1}{n^2\beta_{max}^2}\right]^{-1}\int\left(1-\frac{1}{n^2\beta(E_k)^2}\right)E_k^{0.46}dE_k$$

has been calculated for various values of n and initial values β_{max} and is given in the table below. For the calculated values E_k was in units of hundreds of keV.

	n		Q		
β	1.2	1.3	1.4	1.5	1.6
.667				0	.077
.714			0	.142	.212
.769		0	.290	.442	.442
.833	0	.600	.892	1.00	.813
.850	.322	.971	1.24	1.37	.999
.890	1.63	2.36	2.55	2.50	1.63

The above table shows that for $\beta=0.89$ the contribution of the factor Q to Cherenkov radiation production in a conical lens emitter peaks for indices of refraction in the range 1.3 to 1.5. Total Cherenkov radiation production for a given material will depend both on Q and on the material density D. The following table gives the quantity Q/D for several emitter materials for $\beta=0.89$.

Material	n	D	Q/D
NaF	1.335	2.558	.997
LiF	1.45	2.60	.973
CaF_2	1.445	3.18	.796
SiO_2	1.45	2.20	1.14

This table shows that all the emitter materials produce about the same quantity of Cherenkov radiation within a range of ± 20% with fused silica (SiO_2) being somewhat better than the other materials because of its lower density. NaF, LiF, CaF_2, and fused silica were chosed as examples because they have good transmission properties for ultraviolet radiation. Other materials might produce more collectable light if they are lower density and are composed of lower atomic number elements in addition to having acceptable transmission properties in the soft ultraviolet region of the spectrum.

The diameter of a thin slab emitter or fiber optic plate used with spherical collecting optics is not limited by equation 10. For a thin slab smitter 150 used with spherical collecting optics or a fiber optic plate emitter 186 used with spherical collecting optics under the conditions of relation 22, relation 32 determines the relative number of photons produced. Relation 12 imposes a limit on the value of the kinetic energy which can be used as the upper bound for the integral in relation 32 for valies of $n<\sqrt{2}$.

The greatest signal intensity will be produced in a thin slab emitter by operating at the highest value of β that the detector is designed to achieve, β_{max}, and by using the largest value of n that satisfies the right hand side of relation 12, i.e.,

$$n_{max}=\left(1+\frac{1}{\beta_{max}^2}\right)^{\frac{1}{2}}.$$

Lower values of n will lower the total emission of light because, for a given β and diameter d, fewer photons are produced per electron as n decreases. Higher values of n will lower total emission of light because β must be reduced which again reduces the number of Cherenkov photons per electron. For example, in a detector where the potential between the plate of the oscillator can be as high as 600keV, $\beta_{max}=0.89$ and $n_{max}=1.5$. In practice it may be necessary to use somewhat lower values of β or n to efficiently collect the light with low f number collecting optics.

For a fiber optic plate emitter 186 used with a spherical optical system under the conditions of relation 21, relation 32 also determines the number of photons produced, but the upper limit on electron kinetic energy is determined by relation 20 which imposes a lower value for the upper bound on the integral of relation 32 than is imposed by relation 12. When relation 12 applies, the intensity of the light that can be obtained from a fiber optic plate emitter will always be lower than the maximum intensity of the light that can be obtained from a thin slab emitter made from the same material as the fibers. This is because the number of photons per electron will be smaller since β is smaller. However, the image resolution is improved because the image plane of a fiber optic plate emitter is better defined than with a thin slab emitter.

The maximum diameter d of the entrance surface of both the thin slab and fiber optic emitters is limited only by the constraint imposed by equation 5 on the maximum diameter of the cahtode for a given degradation of response time. Hence, the thin slab and fiber optic emitters when used with spherical collecting optics may be constructed with a larger diameter entrance surface to produce more light by Cherenkov radiation than conical emitters with the same time resolution.

The light collected from the emitter and focused onto a photodetector such as image converter camera 45 by the optical system must be of sufficient intensity to excite the photodetector. An image converter streak camera with an image intesifier, commercially available from John Hadland, Photographic Limited, Newhouse Laboratories, Bovington, Herts, England as model Imacon 675 has a photocathode therein and is sensitive enough to detect a single photoelectron emitted from such photocathode. The Imacon 675 camera can be supplied with a photocathode which converts into photoelectrons about 30 percent of the photons of light in the spectral range in which Cherenkov radiation is transmitted by the optical system of the x-ray detector. One photocathode for the Imacon 675 camera which gives this efficiency is a bialkali K-Cs-Sb material which has an RCA spectral response designation of 133. The Imacon 675 camera has a resolution of 6 line pairs per millimeter and when used in the sweep mode, a maximum sweep speed of the electron beam of the image intensifier of 35 mm/nanosecond which is equivalent to a time resolution of better than 5 picoseconds. The minimum spot size produced by the image intensifier for a single photoelectron emitted from the camera photocathode is about 62.5 μm in diameter. The intensity of light from the spot is sufficient to produce a film density of one on ASA 3,000 speed film at the highest gain of the image intensifier. Thus, at its fastest sweep speed and maximum gain, the Imacon 675 camera with image intensifier requires 1.4×10^3 photons/nanosecond focused to a spot on the photocathode of the camera to produce a streak with a width of 62.5 μm and an average film density of one on ASA 3,000 speed film. For the Imacon 675 camera with image intensifier to produce at its fastest sweep speed and maximum gain a streak with a width of 0.5 cm and an average film density of one on SAS 3,000 speed film requires a flux of 8.4×10^4 photons/nanosecond on the photocathode of the camera.

If x-ray detectors 10' and 110 are used to diagnose the x-ray emission from a laser driven fusion pellet, it is believed these detectors should be responsive to x-ray flux levels as low as one joule per nanosecond into 4π steradians. If cathode 34 of detector 10' has a diameter of 2.08 mm and is located 50 cm from a fuel pellet 12 which emits x-radiation of one joule per nanosecond into 4π steradians with an average x-ray photon energy of 2 keV, then the number of photons impinging on cathode 34 will be 3.1×10^9 photons/nanosecond. If cathode 34 has an efficiency of 1 percent for converting the photons of x-rays to emitted electrons, then the number of electrons emitted from cathode 34 will be 3.1×10^7 electrons/nanosecond. If conical emitter 38 is made of NaF with an average index of refraction of 1.335 in the spectral range of interest and a density of 2.558 g/cm^3 and the initial veoocity β if electrons striking the emitter is 0.89, then each electron will produce about 6.8 photons of Cherenkov radiation in the range between 3,000 to 5,000 angstroms for a total of 2.1×10^8 photons/nanosecond. If 1 percent of these photons of emitted light is collected and focused by the conical optical system onto a spot with a diameter of 50 μm on the photocathode of the Imacon 675 camera, then 2.1×10^6 photons/nanosecond of light will be focused to essentially a point on the photocathode of the image converter camera. This is about 1500 times more light than is required by the Imacon 675 camera with image intensifier to produce a film density of one on ASA 3,000 speed film at the fastest sweep speed and highest gain of the camera. Thus, the intensity of the light produced by a single spot intensity detector 10' embodying this invention is more than adequate to be detected and may need to be attenuated.

If a grazing incidence mirror is used to produce an image on cathode 34 of image detector 110, the amount of x-ray energy reaching the cathode will be at least an order of magnitude less than for direct illumination of the cathode by the x-ray source as in detector 10'. If grazing incidence mirrors image an x-ray flux of 5×10^8 photons/nanosecond onto cathode 34 and the cathode conversion efficiency to electrons is 1 percent, then 5×10^6 electrons/nanosecond will be ejected from cathode 34. If thin slab emitter 128 is made of fused silica with an average index of refraction of 1.47 in the spectral range of 3,000 to 5,000 angstroms, the fused silica has a density of 2.20 g/cm^3 and the initial velocity β of electrons striking the cathode of 0.89, then each electron will emit an average of 16.2 photons of Cherenkov radiation in the range between 3,000 and 5,000 angstroms for a total Cherenkov emission of 8.1×10^7 photons/nanosecond of light. If 20 percent of these photons of light are collected and imaged by the low f number spherical optic system of detector 110 to produce a 0.5 cm image on a 50 μm wide entrance slit 44 of the Imacon 675 camera, then about 2×10^5 photons/nanosecond will be imaged onto the photocathode of the camera 45. Since this is greater than the 8.4×10^4 photons per nanosecond of light required by the Imaco 675 image converter camera to produce a streak of average film density of one on ASA 3,000 speed film, the signal intensity produced by image detector 110 will be adequate for use at an x-ray flux level of one joule/nanosecond into 4π steradians with cathode 34 of the detector located 50 cm from the target.

The intensity of the light produced by detectors embodying this invention may also be increased by positioning cathode 34 closer to fuel pellet 12. X-ray intensity increases as the inverse square of the distance from the target decreases for direct illumination of the cathode 34 by the target. Moreover, the intensity of the light produced by detectors embodying this invention may be increased at the expense of time resolution. For example, instead of sweeping an Imacon 675 camera with intensifier at its fastest speed of 35 milliliters per nanosecond which can give a resolution of a little better than 5 picoseconds, the camera could be swept at half this speed to give a resolution of 10 picoseconds with twice the signal intensity. Similarly, with two dimension "snapshots" using a Kerr cell optical shutter, the average signal intensity will be directly proportional to the amount of time the shutter stays open.

While at least some of the detectors embodying this invention are capable of detecting x-ray fluxes as low as one joule per nanosecond into 4π steradians, it is believed laser fusion targets which produce nuclear yields on the order of the laser energy with which they are irradiated will emit considerable greater x-ray

fluxes. The peak emission from such targets is expected to be as high as one joule per ten picoseconds or a factor of more than one hundred above the threshold detection level of x-ray detectors 10' and 110 embodying this invention. In general, the higher the level of the x-ray flux, the greater the flexibility in using the x-ray detectors of this invention. When the quantity of x-rays is greater, it is easier to select limited regions of the x-ray spectrum for observation without reducing the intensity of the light produced by the detectors of this invention to an undetectable level. It also becomes possible to produce larger images at entrance slit 44 which can be better resolved after being intensified by image converter camera 45 and to split the light beam several times to obtain a series of snapshots separated in time without reducing the intensity of each segment of the light beam below a detectable level.

Detectors embodying this invention may also be used to analyze other intense x-ray sources such as targets irradiated by electron beams or x-ray lasers and the emitter and associated collecting and focusing or imaging optics of this invention may also be used to analyze fluxes of charged particles accelerated to relativistic velocities such as those produced by atomic particle accelerators.

I claim:

1. An x-ray detector comprising, a plurality of cathodes each adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by each of said cathodes to a relativistic velocity, a Cherenkov emitter associated with each of said cathodes and receiving electrons from its associated cathode after the electrons have been accelerated by said electron accelerator and emitting light, and an optical system associated with each of said Cherenkov emitters for collecting and focusing at least part of the light from its associated Cherenkov emitter on a photodetector, and a photodetector for detecting at least part of the light collected by said optical systems from said Cherenkov emitters.

2. The detector of claim 1 wherein said Cherenkov emitters comprise an emitter lens having a plane entrance face through which accelerated electrons pass which is perpendicular to the axis of said emitter lens and a conical exit surface from which light emitted by the accelerated electrons passes, said conical exit surface having a half angle chosen so that light rays within a given range of wavelengths which are emitted in a plane defined by the axis of said emitter lens and any radius vector of said emitter lens perpendicular to the axis thereof will be refracted by the conical surface into rays of light substantially parallel to the optical axis of said emitter lens.

3. The detector of claim 2 wherein said optical systems comprise a collector lens on the same optical axis as said emitter lens and receiving at least part of the light exiting from the conical surface of said emitter lens, said collector lens having a central plane surface through which parallel rays of light from said conical surface of said emitter lens pass and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said conical surface of said emitter lens such that a fraction of the total light coming from said conical surface of said emitter lens emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

4.An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, and said electron accelerator comprises a pair of parallel plates of an electrically conductive material with one of said plates having said cathode thereon and the other of said plates engaging the entrance face of said Cherenkov emitter through which accelerated electrons enter into said Cherenkov emitter.

5. The detector of claim 4 wherein at least part of said other plate of said electron accelerator is deposited on said entrance face of said Cherenkov emitter.

6. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, imaging means forming an image of the source of x-rays, and means producing a magnetic field parallel to the desired direction of axial acceleration of electrons by said electron accelerator, said electron accelerator and said cathode being within said magnetic field such that said magnetic field decreases the magnitude of the transverse excursion of electrons emitted from said cathode, whereby the image resolution of the detector is improved.

7. The detector of claim 6 wherein said means producing a magnetic field comprises a solenoid coil surrounding said cathode and said electron accelerator.

8. The detector of claim 7 wherein said imaging means comprises grazing incidence mirrors.

9. The detector of claim 6 wherein said photodetector comprises an image converter camera.

10. The detector of claim 6 wherein said photodetector comprises a camera with an image intensifier and a shutter provided by an optically triggered Kerr cell controlled by a laser pulse less than 100 picoseconds in duration.

11. The detector of claim 4 which also comprises imaging means forming an image of the source of x-rays and said photodetector comprises a camera with an image intensifier and a shutter provided by an optically triggered Kerr cell controlled by a laser pulse.

12. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, and said Cherenkov emitter comprises an emitter lens having a plane entrance face through which accelerated electrons pass which is perpendicular to the axis of the lens and a conical exit surface from which light emitted by the accelerated electrons passes, said conical exit surface having a half angle chosen so that light rays within a given range of wavelengths which are emitted in a plane defined by the axis of the lens and

any radius vector of the lens perpendicular to the axis thereof will be refracted by the conical surface into rays of light substantially parallel to the optical axis of said emitter lens.

13. The detector of claim 12 wherein said optical system comprises a collector lens on the same optical axis as said emitter lens and receiving at least part of the light exiting from the conical surface of said emitter lens, said collector lens having a central plane surface through which parallel rays of light from said conical surface of said emitter lens enter and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said conical surface of said emitter lens such that a fraction of the total light coming from said conical surface of said emitter lens emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

14. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, and said Cherenkov emitter comprises an emitter prism having a plane entrance face through which accelerated electrons pass which is perpendicular to the axis of said emitter prism and a conical reflecting surface from which light emitted by the accelerated electrons is reflected, said conical reflecting surface having a half angle chosen so that light rays which are emitted in a plane defined by the axis of said emitter prism and any radius vector of said emitter prism perpendicular to the axis thereof will be reflected by said conical reflecting surface into rays of light substantially parallel to the optical axis of said emitter prism.

15. The detector of claim 14 wherein said optical system comprises a collector lens on the same optical axis as said emitter prism and receiving at least part of the light reflected by said conical reflecting surface of said emitter prism, said collector lens having a central plane surface through which parallel rays of light from said conical reflecting surface of said emitter prism enter and a smooth surface surrounding said plane surface and having a curvature to coallect diverging rays of light from said emitter prism such that a fraction of the total light coming from said emitter prism emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

16. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, and said Cherenkov emitter comprises a thin slab emitter and the relativistic velocity of electrons accelerated by said electron accelerator and impinging on the entrance face of said thin slab emitter is both greater than one over the index of refraction of said thin slab emitter and less than the square root of the quantity of one over the square of the index of refraction of said thin slab emitter minus one.

17. The detector of claim 16 wherein said optical system comprises first and second conical mirrors constructed and arranged to receive and reflect into parallel rays of light at least a fraction of the light emitted in said thin slab emitter in a plance defined by the optical axis of said thin slab emitter and a radius vector perpendicular to the axis of said thin slab emitter, the half angle of said first conical mirror being equal to the quantity of the half angle of said second conical mirror minus one half of the angle at which light emitted in said plane emerges from the exit face of said thin slab emitter.

18. The detector of claim 17 wherein said optical system comprises a collector lens on the same optical axis as said conical mirrors and receiving at least part of the light exiting from said second conical mirror, said collector lens having a central plane surface through which parallel rays of light from said second conical mirror enter and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said second conical mirror such that a larger fraction of the total light coming from said second conical mirror emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

19. The detector of claim 16 which also comprises imaging means forming an image of the source of x-rays and means producing a magnetic field parallel to the desired direction of axial acceleration of electrons by said electron accelerator, said electron accelerator and said cathode being within said magnetic field such that said magnetic field decreases the magnitude of the transverse excursion of electrons emitted from said cathode, whereby the image resolution of the detector is improved.

20. The detector of claim 19 wherein said optical system comprises a doubly reflecting, collecting and imaging system having a first concave mirror and a second convex mirror for collecting and imaging light leaving the exit face of said thin slab emitter.

21. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, a spherical optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, said Cherenkov emitter comprises a fiber optic plate having a plurality of transparent fibers each embedded in an opaque cladding having a lower index of refraction than that of said fibers, each said fiber being constructed and arranged with an entrance face and an exit face essentially perpendicular to the longitudinal axis of said fiber and said longitudinal axis extending essentially parallel to the path of accelerated electrons entering said fiber through said entrance face, and the electrons accelerated by said electron accelerator and entering said transparent fibers of said fiber optic plate having a relativistic velocity which is less than one over the index of refraction of said opaque cladding, less than the square root of the quantity of one over the square of the index of refraction of said transparent fibers minus one, and also greater than one over the index of refraction of said transparent fibers.

22. An x-ray detector comprising, a cathode adapted to emit electrons when irradiated by x-rays, imaging means forming on said cathode an image of the source of x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, an optical system for collecting at least part of the light from said Cherenkov emitter, a photodetector for detecting at least part of the light collected by said optical system from said Cherenkov emitter, means producing a magnetic field parallel to the desired direction of axial acceleration of electrons by said electron accelerator, said electron accelerator and said cathode being within said magnetic field such that said magnetic field decreases the magnitude of the transverse excursion of electrons emitted from said cathode such that the image resolution of the detector is improved, said Cherenkov emitter comprises a fiber optic plate having a plurality of transparent fibers embedded in an opaque cladding having a lower index of refraction than that of said fibers, and the electrons accelerated by said electron accelerator and entering said transparent fibers of said fiber optic plate having a relativistic velocity which is less than one over the index of refraction of said opaque cladding, less than the square root of the quantity of one over the square of the index of refraction of said transparent fibers minus one, and also greater than one over the index of refraction of said transparent fibers.

23. The detector of claim 22 wherein said optical system comprises a doubly reflecting, collecting and imaging system similar to a Burch all-reflecting microscope objective and having a first concave mirror and a second convex mirror for collecting and imaging light leaving the exit face of said fiber optic plate.

24. The detector of claim 22 wherein said means producing a magentic field comprises a solenoid coil surrounding said cathode and said electron accelerator.

25. The detector of claim 22 wherein said photodetector comprises an image converter camera.

26. The detector of claim 22 wherein said photodetector comprises a camera with an image intensifier and a shutter provided by an optically triggered Kerr cell controlled by a laser pulse.

27. An x-ray detector comprising a cathode adapted to emit electrons when irradiated by x-rays, an electron accelerator for accelerating electrons emitted by said cathode to a relativistic velocity, a Cherenkov emitter receiving accelerated electrons from said electron accelerator and emitting light, imaging means forming an image on said cathode of the source of such x-rays, and means producing a magnetic field parallel to the desired direction of axial acceleration of electrons by said electron accelerator, said electron accelerator and said cathode being within said magnetic field such that said magnetic field decreases the magnitude of the transverse excursion of electrons emitted from said cathode whereby the image resolution of the detector is improved.

28. The detector of claim 27 which also comprises an optical system for collecting at least part of the light from said Cherenkov emitter and reconstructing an image of the source of such x-rays, and a photodetector for recording the reconstructed image produced by said optical system.

29. The detector of claim 28 wherein said photodetector comprises a camera with an image intensifier and a shutter provided by an optically triggered Kerr cell controlled by a laser pulse having a duration of less than one hundred picoseconds.

30. A detector of a flux of high energy charged particles comprising a Cherenkov emitter receiving at least a portion of the charged particles and emitting light, an optical system for collecting at least a portion of the light from said Cherenkov emitter, a photodetector having a time resolution of less than 100 picoseconds for detecting and recording at least part of the light collected by said optical system, said Cherenkov emitter comprising an emitter lens having a plane entrance face through which charged particles pass which is essentially perpendicular to the axis of said emitter lens and a conical exit surface from which light emitted by said charged particles passes, said conical exit surface having a half angle chosen so that light rays within a given range of wave lengths which are emitted in a plane defined by the axis of said emitter lens and any radius vector of said emitter lens perpendicular to the axis thereof will be refracted by the conical surface into rays of light substantially parallel to the optical axis of said emitter lens.

31. The detector of claim 30 which comprises a plurality of said Cherenkov emitters and an optical system associated with each of said Cherenkov emitters for collecting and focusing at least part of the light from its associated Cherenkov emitter on a photodetector.

32. The detector of claim 30 wherein said optical system comprises a collector lens on the same optical axis as said emitter lens and receiving at least part of the light exiting from the conical surface of said emitter lens, said collector lens having a central plane surface through which parallel rays of light from said conical surface of said emitter lens pass and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said conical surface of said emitter lens such that a fraction of the total light coming from said conical surface of said emitter lens emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

33. A detector of a flux of high energy charged particles with relativistic velocities comprising a Cherenkov emitter receiving at least a portion of the charged particles and emitting light, an optical system for collecting at least a portion of the light from said Cherenkov emitter, a photodetector having a time resolution of less than 100 picoseconds for detecting and recording at least part of the light collected by said optical system, and said Cherenkov emitter comprising an emitter prism having a plane entrance face which is perpendicular to the axis of said emitter prism and through which at least a portion of the charged particles pass and a conical reflecting surface from which light emitted by the charged particles is reflected, said conical reflecting surface having a half angle chosen so that light rays which are emitted in a plane defined by the axis of said emitter prism and any radius vector of said emitter prism perpendicular to the axis thereof will be reflected by said conical reflecting surface into rays of light substantially parallel to the optical axis of said emitter prism.

34. The detector of claim 33 wherein said optical system comprises a collector lens on the same optical axis as said emitter prism and receiving at least part of the light reflected by said conical reflecting surface of said emitter prism, said collector lens having a central plane surface through which parallel rays of light from

said conical reflecting surface of said emitter prism enter and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said emitter prism such that a fraction of the total light coming from said emitter prism emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

35. A detector of a flux of high energy charged particles with relativistic velocities comprising a Cherenkov emitter receiving at least a portion of the charged particles and emitting light, an optical system for collecting at least a portion of the light from said Cherenkov emitter, a photodetector having a time resolution of less than 100 picoseconds for detecting and recording at least part of the light collected by said optical system, said Cherenkov emitter comprises a thin slab emitter and the relativistic velocity of the charged particles impinging on the entrance face of said thin slab emitter is both greater than one over the index of refraction of said thin slab emitter and less than the square root of the quantity of one over the square of the index of refraction of said thin slab emitter minus one.

36. The detector of claim 35 wherein said optical system comprises first and second conical mirrors constructed and arranged to receive and reflect into parallel rays of light at least a fraction of the light emitted in said thin slab emitter in a plane defined by the optical axis of said thin slab emitter and a radius vector perpendicular to the axis of said thin slab emitter, the half angle of said first conical mirror being equal to the quantity of the half angle of said second conical mirror minus one half of the angle at which light emitted in said plane emerges from the exit face of said thin slab emitter.

37. The detector of claim 36 wherein said optical system comprises a collector lens on the same optical axis as said conical mirrors and receiving at least part of the light exiting from said second conical mirror, said collector lens having a central plane surface through which parallel rays of light from said second conical mirror enter and a smooth surface surrounding said plane surface and having a curvature to collect diverging rays of light from said second conical mirror such that a larger fraction of the total light coming from said second conical mirror emerges from said collector lens in rays of light substantially parallel to the optical axis of said collector lens.

38. The detector of claim 33 which also comprises imaging means forming an image of the source of the charged particles and wherein said optical system comprises a doubly reflecting, collecting and imaging system having a first concave mirror and a second convex mirror for collecting and imaging light leaving the exit face of said thin slab emitter.

39. A detector of a flux of high energy charged particles with relativistic velocities comprising a Cherenkov emitter receiving at least a portion of the charged particles and emitting light, an optical system for collecting at least a portion of the light from said Cherenkov emitter, a photodetector having a time resolution of less than 100 picoseconds for detecting and recording at least part of the light collected by said optical system, and said Cherenkov emitter comprises a fiber optic having a plurality of transparent fibers embedded in an opaque cladding having a lower index of refraction than that of said fibers, each said fiber being constructed and arranged with an entrance face and an exit face essentially perpendicular to the longitudinal axis of said fiber and said longitudinal axis extending essentially parallel to the path of charged particles entering said fiber through said entrance face, and said charged particles upon entering said fibers of said optic plate having a relativistic velocity which is less than one over the index of refraction of said opaque cladding, less than the square root of the quantity of one over the square of the index of refraction of said transparent fibers minus one, and also greater than one over the index of refraction of said transparent fibers.

40. The detector of claim 39 which also comprises imaging means forming an image of the source of such charged particles and means producing a magnetic field parallel to the longitudinal axis of said fibers of said fiber optic plate and constructed and arranged so that such charged particles pass through such magnetic field prior to entering said transparent fibers to decrease the magnitude of the transverse excursion of such charged particles so as to improve the image resolution of the detector.

41. The detector of claim 39 wherein said optical system comprises a doubly reflecting, collecting and imaging system similar to a Burch all-reflecting microscope objective and having a first concave mirror and a second convex mirror for collecting and imaging light leaving the exit face of said fiber optic plate.

42. A detector of a flux of high energy charged particles with relativistic velocities comprising a Cherenkov emitter receiving at least a portion of the charged particles and emitting light, an optical system for collecting at least a portion of the light from said Cherenkov emitter, a photodetector having a time resolution of less than 100 picoseconds for detecting and recording at least part of the light collected by said optical system, said Cherenkov emitter comprises a fiber optic plate having a plurality of transparent fibers each embedded in an opaque cladding having a lower index of refraction than that of said fibers, each said fiber being constructed and arranged with an entrance face and an exit face essentially perpendicular to the longitudinal axis of said fiber and said longitudinal axis extending essentially parallel to the path of the charged particles entering said fiber through said entrance face, and the charged particles entering said transparent fibers of said fiber optic plate having a relativistic velocity which is less than one over the index of refraction of said opaque cladding, less than the square root of the quantity of one over the square of the index of refraction of said transparent fibers minus one, and also greater than one over the index of refraction of said transparent fibers.

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Rentzepis et al.

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[54] **COMPACT HIGH-INTENSITY PULSED X-RAY SOURCE, PARTICULARLY FOR LITHOGRAPHY**

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[51] **Int. Cl.**[6] **H01S 35/06**

[52] **U.S. Cl.** **378/136**; 378/119

[58] **Field of Search** 378/119, 121, 378/122, 136

[56] **References Cited**

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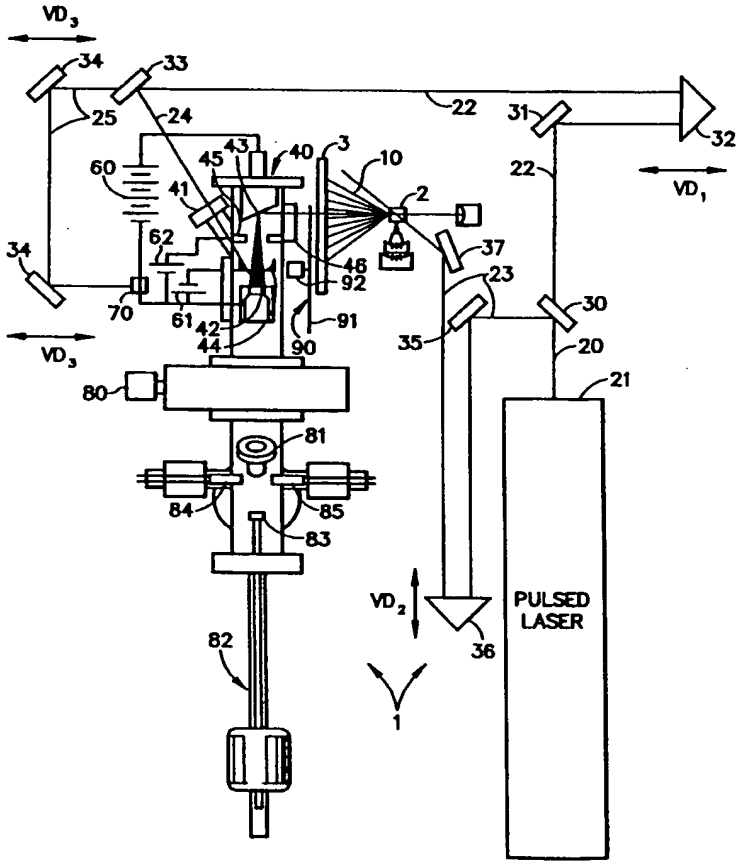
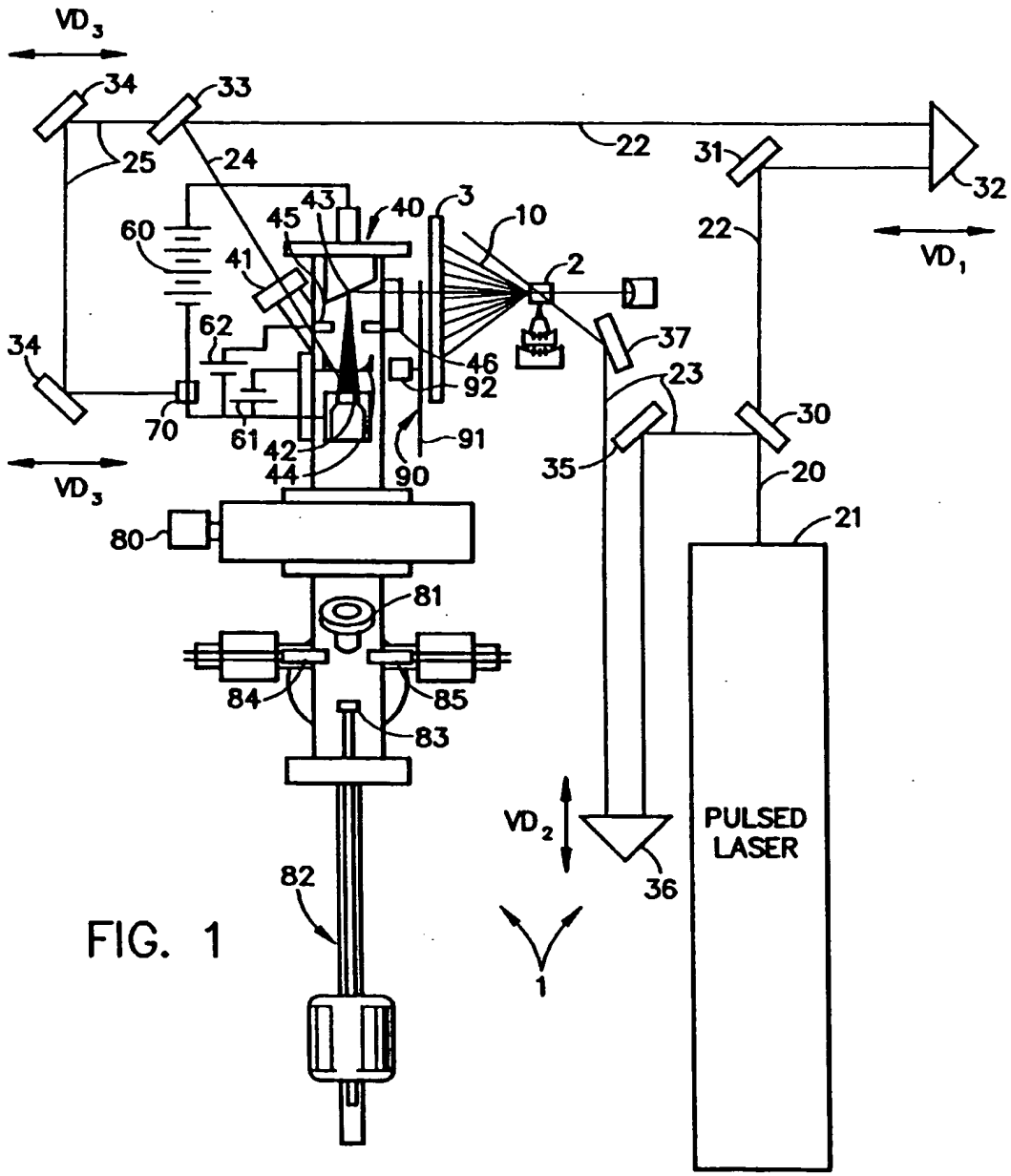
[57] **ABSTRACT**

A photoemissive photocathode, being a metal with a low work function and preferably tantalum-surfaced cesium-antimonide, is illuminated with pulses of 5320 Å laser light, typically 20 psec at a 20 Hz repetition rate, to emit electrons by the photoelectric effect. The emitted electrons are accumulated in a spatial region near the photocathode by a grid electrode. The same laser pulses activate a semiconductor switch, normally an $LiTaO_3$ crystal doped with 2.24% Cu, to apply a high voltage, typically 100 Kv, between the photocathode and an anode. The accumulated electrons are accelerated, and focused, as an electron beam that strikes the anode, typically in a focal spot of less than 0.5 mm diameter. Time-resolved x-ray pulses, typically K band of 20 picoseconds duration with 4–10 microjoules energy each, are produced. A laser-induced pulsed wide-area table-top-size embodiment of the x-ray source reliably generates a 1–10 mW/cm^2 flux of hard, 0.1–1 nm, x-rays from picosecond duration laser pulses, and a 20–40 mW/cm^2 flux of x-rays from 20 ns, 193 nm laser pulses at a pulse repetition rate of 300 Hz minimum, 1,000 Hz typical. The x-ray generation is uniform over a large 20 cm^2 anode area. A mask is placed in direct contact with the anode for lithography.

28 Claims, 2 Drawing Sheets




VD3
34
33
25
24
22
31
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VD1
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45
43
40
3
10
41
2
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46
92
23
30
70
61
42
44
90
91
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VD3
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81
84
85
83
VD2
PULSED LASER
82
36
1

FIG. 1

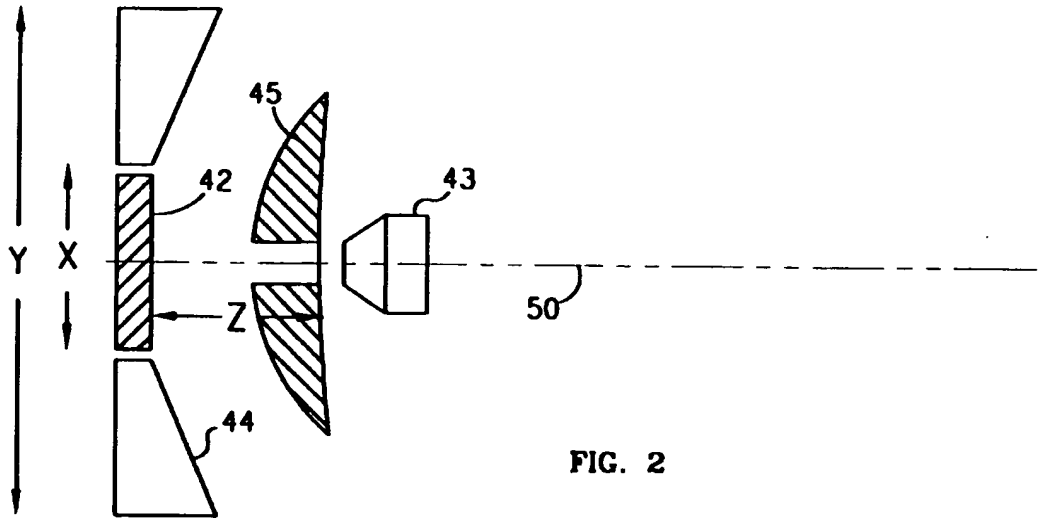
45
42
43
Y
X
Z
50
44

FIG. 2

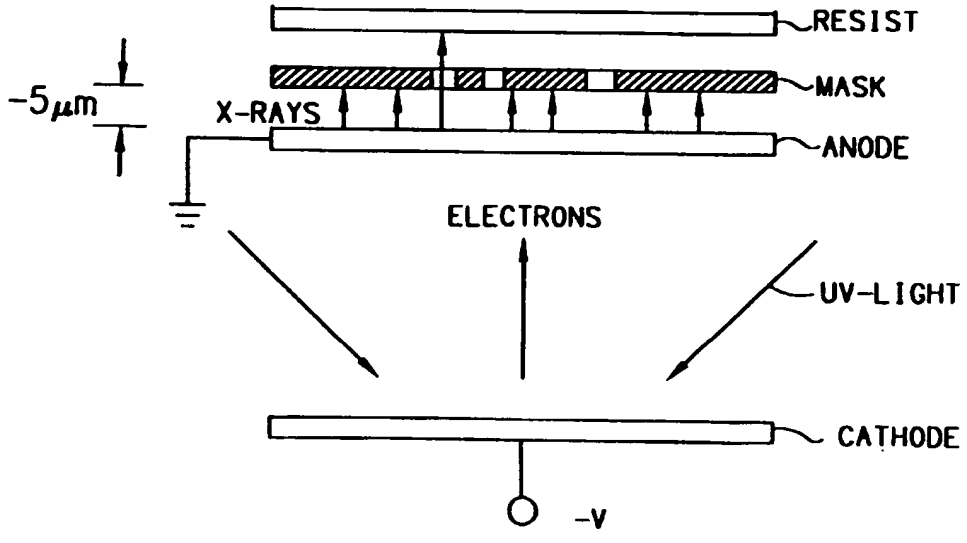
RESIST
MASK
-5μm
X-RAYS
ANODE
ELECTRONS
UV-LIGHT
CATHODE
-V

FIG. 3

COMPACT HIGH-INTENSITY PULSED X-RAY SOURCE, PARTICULARLY FOR LITHOGRAPHY

REFERENCE TO RELATED APPLICATIONS

The present patent application is a continuation-in-part of copending U.S. patent application Ser. No. 07/326,910 filed Mar. 22, 1989 for an ULTRASHORT TIME-RESOLVED X-RAY SOURCE, now issued as U.S. Pat. No. 5,024,058 on Aug. 20, 1991. The inventor of the copending patent application is the selfsame Peter M. Rentzepis who is one of the co-inventors of the present application.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention concerns the generation of x-rays, and particularly time-resolved x-rays having nanosecond and shorter duration. The present invention particularly concerns x-ray sources for lithography, and especially sources providing an energetic flux of hard x-ray radiation over a spatially extended area.

2. Background of the Invention

The present invention generally relates to the production of x-ray radiation, particularly time-resolved pulses of x-ray radiation, and particularly relates to the production of x-ray radiation over a spatially extended area.

2.1 Time-Resolved X-ray Sources

The earliest attempts to produce time-resolved x-rays employed mechanical shutters that moved in front of x-ray sources. For example, transmission of x-rays through x-ray transparent apertures within a rotating apertured disk that was otherwise opaque to x-rays permitted the generation of millisecond x-ray pulses. These millisecond x-ray pulses were too slow to permit the study by x-ray diffraction of any type of molecular phenomena such as reaction, melding, dissociation, or vibration. Millisecond x-ray pulses were, however, sometimes sufficient to permit observation of certain biological phenomena, although not normally at the biomolecular level.

Davanloo et al., *Rev. Sci. Instrum.* 58:2103–2109 (1987) reported constructing an x-ray source capable of producing x-ray pulses of nanosecond (ns) duration. That x-ray source utilized (i) a low impedance x-ray tube, (ii) a Blumlein power source, and (iii) a commutation system for periodically applying power from the Blumlein power source to the x-ray tube. The system yielded 140-mW average power in 15 ns pulses of radiation near 1 Å. That device, and others based on Blumlein-generators, suffers from (i) low repetition rates in the range of 100 hertz, (ii) prospective inability to produce pulses shorter than about 15 nsec, and (iii) low energy efficiency on the order of 25%. The durability in operational use of Blumlein-based sources of x-ray flashes is also uncertain.

More recently, *Science News*, Vol. 134, No. 2: pp. 20 (1989) reported that scientists at Cornell University and the Argonne National Laboratory have developed a device, called an undulator, capable of producing x-ray pulses one-tenth of a billionth of a second (100 picoseconds) in duration. The undulator utilized synchrotron radiation from fast-moving charged particles in an electron storage ring. Because electron storage rings are typically large and expensive, the ring used at Cornell being one half-mile in diameter, the production of bright x-ray flashes by such means is distinctly not adaptable to the scale and budget of a typical materials or biological laboratory.

X-rays have been produced using plasma sources that are energized by lasers. In laser plasma x-ray sources, either a pulsed-infrared (IR) laser or a ultraviolet (UV) excimer laser is used with pulse widths varying from less than 10 picoseconds to 10 nanoseconds. The laser beam is focused on a target where it creates a plasma having a sufficiently high temperature to produce continuous and characteristic x-ray radiation. Major disadvantages of laser plasma x-ray sources include (i) a diffuse, non-point, area of x-ray emission (ii) low efficiency and (iii) low repitition rate.

2.2 X-ray Sources for Lithography

Since the seminal paper by Henry Smith appeared in 1972, the achievement of economical x-ray lithography has been rather elusive. During the intervening years, however, considerable progress in many areas has been made, including development of masks, resists and registration capabilities.

Three main classes of x-ray sources are considered as a possible choice for lithography. Those are electron impact tubes, laser-based plasmas, and synchrotrons. Progress has been made in each of these sources, particularly in laser-driven plasma x-ray sources. Efforts in Japan have been devoted to the development of compact, high density synchrotrons. Even today, each of these sources has its limitations for a practical system.

The most intense sources are the synchrotrons, but so far their price, size and complexity make them prohibitive for use in a production line.

Electron impact tubes are the simplest and cheapest sources. However, their effectiveness is best only in the hard x-ray region. For high current output electron impact tubes must be pulsed because of the extreme heat generated on the anode by electron impact on the anode.

Laser driven x-ray sources have started to appear and show promise.

The requirements for a practical x-ray source for lithography are dependent on development of the other two critical components of the lithographic process—mask and resist. Most of the research and development for x-ray sources is centered in the 0.4–5 nm wavelength range where suitable resists are available. Use of still harder x-rays, 0.1–1.0 nm, would bring additional benefits, such as the possibility of ultrasensitive microsensors for medical and technological applications and, of course, higher resolution lithography permitting a denser layout of semiconductor components.

The present invention will be seen to be concerned with the generation of x-ray pulses for lithography in a manner that is believed to provide several distinct advantages over previous x-ray sources.

2.3 Photoemissive Sources of Electrons

By way of background to the present invention, Lee, et al., in *Rev. Sci. Instrum.*, 56:560–562 (1985) described a laser-activated photoemissive source of electrons. In the laser-activated photoemissive electron source a photocathode is illuminated with high intensity laser light as a means of generating numerous electrons by the photoelectric effect. The electrons emitted from the photocathode are focused in an electrical field, typically produced by electrodes in an electron-gun configuration, in order to produce a high intensity electron beam.

2.4 Rectification of Ultrashort Optical Pulses to Produce Electrical Pulses

By way of further background to the present invention, the rectification of ultrashort optical pulses in order to generate electrical pulses having durations and amplitudes

that are unobtainable by conventional electronic techniques is described by Auston, et al. in the *Annl. Phys. Lett.*, 20: 398–399 (1972). Electrical pulses on the order of 4 amperes in 10 picoseconds are generated by rectification of 1.06 micrometer optical pulses in a $LiTaO_3$ crystal doped with approximately 2.24% Cu ($LiTaO_3$:Cu^{++}).

A doped transmission line, having an absorption coefficient of 60 cm^{-1} and a thickness of 0.2 mm, is bonded with a thin epoxy layer to an undoped crystal in the form of a TEM electro-optic transmission line of 0.5×0.5-mm cross-sectional area. Current pulses are generated by absorption in this transducer of single 1.06 micrometer mode-locked Nd: glass laser pulses, typically of duration 3–15 psec and with an energy of approximately 1 mJ.

The electro-optic transmission line, or switch, operates to conduct current during the presence of laser excitation by action of the macroscopic polarization resulting from the difference in dipole moment between the ground and excited states of absorbing Cu^{++} impurities. Effectively, the electric-optic transmission line, or switch, has a very great number of charge carriers, and is a very good conductor, during the presence of laser excitation. During other times it is a semiconductor and does not conduct appreciable current. The excited-state dipole effect of the transmission line, or switch, is exceptionally fast, on the order of 1 or 2 psec or less.

SUMMARY OF THE INVENTION

The present invention contemplates a compact, high-intensity, inexpensive, reliable, tunable, high-intensity pulsed x-ray (PXR) light source where copious electrons are efficiently produced at a photocathode by the photoelectric effect and then, having been efficiently produced, effectively accelerated and focused in a strong electric field to impinge upon a desired area of an anode, thereby to produce bright x-ray light by bremstrahlung.

In various embodiments an x-ray source in accordance with the present invention can produce pulsed x-ray radiation that is any one or ones of (i) very short (typically 20 ps), (ii) very bright (typically 6.2×10^6 cm^{-2} sr^{-1} at the Ka wavelength (1.54 Å), and/or (iii) very hard (typically 0.1–1 micrometer wavelength). X-ray source in accordance with the present invention are effectively applied in the areas of crystallography, spectrography, and especially lithography. Particularly for lithography applications, a compact wide-area x-ray source can produce from 1 to 40 mW/cm^2 x-ray radiation flux (depending upon the duration and repetition rate of the laser pulses) uniformly over an area (typically circular in shape) that is as large as 20 cm^2. Such an energetic high-intensity pulsed hard x-ray flux over such a large area is manifestly suitable for the masked exposure of photoresists in the production of semiconductors: the x-ray source, mask, resist and semiconductor substrate are placed tight together in simple close contact—obviating any need for focusing.

An x-ray source in accordance with the present invention has (i) a laser for producing a laser beam (a beam of laser light), and (ii) an electron source means, preferably photoemissive, that is capable of producing electrons in response to illumination by the laser beam and which is positioned for illumination by the laser beam. The x-ray source also includes (iii) a high voltage means energized to generate an electric field for accelerating, as an electron beam, the electrons produced by the impinging of the laser beam on the electron source means, and (iv) an electron beam target means positioned to intercept the accelerated electrons (electron beam) in order to produce x-rays in response thereto.

Preferably, the x-ray source further includes a high voltage switching means selectively operable to energize the high voltage means for a selected period of time for accelerating the electron beam during the selected time period to produce an x-ray pulse. Preferably, the high voltage switching means comprises an electrical switch selectively operable to selectively energize the high voltage means in response to, and in synchronism with, the laser beam pulses.

In another preferred embodiment, the x-ray source further includes a means for producing the laser beam as pulses in substantial temporal synchronization with the energization of the high voltage means.

In still another preferred embodiment, the x-ray source includes a field electrode means disposed between the electron source means and the electron beam target means for substantially suppressing the electron beam in response to deenergization of the high voltage means. Preferably, the field electrode means comprises an electrode positioned closer to the electron source means than to the electron beam target means.

In embodiments containing an electrode, it is preferred that the x-ray source further include a means for negatively voltage biasing the electrode relative to the electron source means for substantially maintaining the electrons produced by the electron source means in a region between the electrode and the electron source means in response to deenergization of the high voltage means.

A still further preferred embodiment of the x-ray source of this invention includes a means for directing the laser beam pulses onto a scattering sample (a sample for scattering the x-ray radiation) for energizing the scattering sample substantially simultaneously with illumination of the sample by the x-ray radiation.

Still another preferred embodiment of the x-ray source of this invention includes an x-ray switch means for switching x-rays received from the electron beam target means to produce an x-ray pulse. Preferably, the x-ray switch means comprises an apertured plate, such as a rotating plate, movable to selectively and alternately occlude and to pass the x-rays through an aperture for producing an x-ray pulse.

In one preferred x-ray source in accordance with the present invention, the electron source means comprises a photocathode, the electron beam target means comprises an anode, and the high voltage power supply is connected between the photocathode and the anode for generating the electric field used for accelerating the electrons produced by the photocathode as an electron beam that impinges the anode to produce the x-rays.

In another embodiment, the present invention contemplates a source of x-ray radiation comprising a laser source of laser light, a chamber evacuated to a high vacuum, a photocathode within the chamber for emitting electrons in response to illumination thereof by the laser light, an anode within the chamber spaced apart from the photocathode, and a high voltage source for electrically biasing the anode to a high voltage relative to the cathode for accelerating electrons emitted from the cathode as an electron beam to impinge upon the anode and to produce x-ray radiation. Preferably, a high voltage switch is connected to the high voltage source, the photocathode and the anode, for selectively biasing the anode with high voltage relative to the cathode in synchronization with the illumination of the photocathode by the pulses of laser light. Preferably, the high voltage switch is selectively operable for switching the

biasing of the anode in response to and in synchronization with the pulses of laser light. Preferably, the high voltage switch comprises a semiconductor switch responsive to the pulses of laser light.

Preferably, the source of x-ray radiation of this invention further includes (i) a grid electrode within the chamber between the anode and the photocathode, and (ii) a voltage source for electrically biasing the grid electrode with a voltage, lower than the high voltage, for jointly limiting the drift of the emitted electrons under the space charge effect to a region of the chamber proximate the anode when the anode is not electrically biased with the high voltage, and (iii) a high voltage switch connected to the high voltage source and the photocathode for selectively applying the high voltage between the anode and the photocathode to produce pulses of emitted electrons accelerated from the photocathode through the grid electrode to impinge the anode, producing pulses of x-ray radiation.

The present invention still further contemplates an improvement to the photocathode element of the laser-activated, photoemissive, electron source. A metal, is preferably deposited on, or is alternatively mixed in bulk with, a semiconductor. The metal is preferably tantalum (Ta), copper (Cu), silver (Ag), aluminum (Al) or gold (Au) or oxides or halides of these metals, and is more preferably tantalum. The depositing is preferably by sputtering or annealing, and is preferably by annealing. The semiconductor is preferably cesium (Cs) or cesium antimonide (Cs_3Sb) or gallium arsenide (GaAs), and is more preferably cesium antimonide. A photocathode so formed exhibits efficient electron emission by the photoelectric effect and improved longevity.

In another embodiment, the present invention contemplates a method of producing x-ray radiation comprising illuminating a photocathode in a high vacuum with laser light, preferably at intermittent intervals, in order to produce electrons therefrom by the photoelectric effect and accelerating the produced electrons in a high voltage electric field to impinge on an anode in the high vacuum to produce x-ray radiation.

In an embodiment particularly suited for use in x-ray lithography the x-ray source of the present invention includes a laser light generator for producing laser light illumination over a spatially extended area and a spatially extended photoemitter means intercepting the laser light illumination over the spatially extended area in order to produce electrons by the photoelectric effect over the same spatially extended area. A high voltage source generates an electric field for accelerating the produced electrons as a wavefront of electrons, the wavefront again occurring over the spatially extended area. A spatially extended metal foil is positioned to intercept the wavefront of electrons over the spatially extended area of such wavefront, and, responsively to this interception, for producing x-rays. The x-rays so produced over a spatially extended area are particularly useful for lithography, including in the masked exposure of photoresist upon a semiconductor substrate where the substrate, photoresist, and mask are tight against (i.e., at a separation that is typically ≤ 5 micrometers) the metal foil.

These and other aspects and attributes of the present invention will become increasingly clear by reference to the following drawings and accompanying specification.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram showing a preferred embodiment of an ultrashort, picosecond, time-resolved x-ray source in accordance with the present invention in operational use for performing an x-ray diffraction experiment.

FIG. 2 is a cross-sectional plan view of the photocathode, anode, grid electrode and focusing plates within the preferred embodiment of an x-ray source shown in FIG. 1.

FIG. 3 is an enlarged cross-sectional view of the cathode and anode of an alternate, through-path-transmitting, x-ray source in accordance with the present invention in position, and in use, for lithography.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention contemplates the production of x-rays in a high vacuum by (i) illuminating a photoemissive photocathode with high intensity laser light to cause the emission of copious electrons by the photoelectric effect, (ii) accelerating, and preferably focusing, the emitted electrons in and by a high voltage electric field established between the photocathode and an anode so as to form an electron beam, and (iii) striking the anode, which also serves as an electron beam target, with the accelerated (and focused) electron beam in order to produce x-ray radiation.

The present invention further contemplates the production of time-resolved x-rays, including nanosecond and shorter duration x-ray pulses. In order to do so multiple independent and separable techniques are employed.

First, the laser is cycled in operation so as to produce time-resolved light pulses, typically 20 picosecond light pulses at a repetition rate of 20 Hz. Alternatively, a laser producing 80 picosecond duration light pulses may be cycled at an 82 Mhz rate, giving an approximate 0.66% duty cycle. Typically pulses of an intermediate duration, nominally 10 picoseconds, are produced at an intermediate frequency, nominally 1 kHz.

Second, the electrons periodically emitted from the photocathode in response to the periodic laser light pulses are preferably accumulated in a spatial region near the photocathode—overcoming the normal dispersion of these electrons throughout the region between the photocathode and the anode which would be expected due to the space charge effect—by use of a grid electrode that is positioned between the photocathode and the anode. The grid electrode, typically biased at about 3 kV, functions to accumulate the emitted electrons in bunches. However, it so functions only upon, and during such times, that the much greater high voltage between the photocathode and the anode is switched off.

In accordance with an important third aspect of the present invention, the high voltage, typically approximately 100 Kv, between the photocathode and the anode is preferably switched on and off, preferably in a semiconductor switch that is responsive to the laser light pulses. The high voltage is switched on for a time period that spans the period of photoemission, and which is typically substantially coincident with the period of photoemission.

The use of a grid electrode, and the switching of the high voltage, are both optional: it is sufficient to create time-resolved x-rays only that the laser should be pulsed. However,use of the grid electrode and switching of the high voltage helps to keep the emitted electrons tightly grouped in "packets". When these electron packets ultimately strike the anode then the resulting time-resolved x-ray pulse is not appreciably longer than the laser light pulse.

In the preferred time-resolved x-ray source in accordance with the present invention each of the activities of (i)

photoemission, (ii) accumulation of photoemitted electrons, and (iii) switching of the high voltage is appropriately temporally sequenced and phased. Each laser light pulse (i) photoemissively generates abundant electrons which are (ii) accumulated in a narrow spatial region between the photocathode and anode and then, the high voltage being switched on, (iii) accelerated and focused into a short-duration time-resolved electron beam. The short-duration electron beam is typically equally as short as the laser light pulse from which it arose, or approximately 20 picoseconds in duration. It strikes the anode x-ray target in a tightly focused spot, typically of less than 0.5 mm diameter, producing an x-ray pulse of approximately 20 picoseconds duration and approximately 4–50 millijoules energy.

The picosecond x-ray pulse itself may be further gated, such as by having its leading or trailing edges truncated by passage through the x-ray transparent apertures of a rapidly rotating apertured plate.

The energy of the time-resolved x-ray pulses is a function of the high voltage, and is typically controlled to be of K, L, or M bands. Normally a high voltage of 100 KV is used to produce K band x-ray pulses. The intensity of the x-ray pulses is a function of (i) the intensity and duration of the laser light pulses, (ii) the efficiency of the photocathode, and (iii) the quantity of electrons that are accumulated between the grid electrode and the photocathode before being accelerated as a packet to the anode. X-ray pulses more intense than 4–10 microjoules, shorter than 20 picoseconds, and/or at duty cycles greater than 0.66% are possible.

The time-resolved x-ray source in accordance with the present invention is beneficially operated at pulsed x-ray energies, intensities, and duty cycles that do not require external cooling of the source. Particularly when the source used for photolithography then a photoresist is normally exposed to many individual x-ray pulses. Because of the reasonable energy within each of these pulses (roughly equivalent to a flashed synchrotron radiation x-ray source, the brightest previously known source), the total elapsed chronological and cumulative exposure times are reasonable in support of manufacturing production of semiconductors.

In use of the x-ray source in accordance with the present invention for x-ray spectroscopy, the picosecond x-ray pulses are preferably directed to illuminate with x-ray light a scattering sample that is excited in its energy state by the selfsame laser light pulses, appropriately time phased, that originally gave rise to the x-ray pulse. X-ray spectroscopy is thus promoted not only by the low cost and compact availability of x-ray pulses that are sufficiently short and sufficiently intense so as to permit observation by x-ray diffraction of the successive stages of time-variant molecular reactions, but is also promoted by a capability of synchronization of these reactions to the very x-ray pulses that permit the reactions to be observed in the first place. (It can alternatively be considered that the x-ray pulses are synchronized to the reactions.)

An x-ray source in accordance with the present invention has utility based on its (i) ability to produce time-resolved x-rays from continuous to picosecond and shorter duration, (ii) excellent focus providing an x-ray emission spot size that is typically less than 0.5 mm in diameter, (iii) ability to use different wavelengths of laser light that result in differing quantities of emitted electrons and intensities of resultant x-rays, including x-rays of microjoule intensities in picosecond intervals, (iv) capability to operate with over a range of high voltages in order to produce x-rays in the K, L, and M bands, (v) substantial lack of heat build-up when operated at a low duty cycle, (vi) compact, desk-top, size and (vii) general reliability and low cost.

A preferred embodiment of a time-resolved x-ray source in accordance with the present invention for producing picosecond duration K band x-ray pulses is diagrammatically illustrated in operational use for x-ray spectroscopy in FIG. **1**. A scattering sample **2** is illuminated with ultrashort time-resolved x-ray pulses **10**, typically of 20 to 50 picoseconds duration, to produce an x-ray image on an x-ray imaging device **3**. The x-ray imaging device **3** is typically a photographic plate, or image intensifier, positioned in the Laue backscattering configuration. A goniometer (not shown), or other instrument for measuring angles, helps to align the position of scattering sample **2** with the x-ray beam **10** and with the x-ray imaging device **3**.

The production of time-resolved x-rays **10** in x-ray source **1** commences with a laser beam **20** that is generated in a pulsed laser **21**. The laser **21** is typically of the Nd-YAG type. One such type laser is Spectrophysics Model 3000 YAG laser. It is capable of producing 80 picosecond duration laser pulses at a repetition rate of up to 82 Mhz. A preferred pulsed laser **21** available from Quantel International is capable of producing up to 20 picosecond duration laser light pulses at a repetition rate of 20 Hz. Each laser pulse is of green light (approximately 5320 Å), and contains about 4 millijoules energy. The nominal 10 ps pulses (and even more commonly 6 ps pulses) at the nominal 1 kHz repetition rate (and even more commonly at any repetition rate from 300 Hz to 1 kHz) may be produced at, for example, a 193 nm wavelength with, for example, a commercially-available ArF excimer laser.

The laser light pulses **20** produced by pulsed laser **21** are split in first beamsplitter **30** into pulsed laser light beam lines **22, 23**. The intensity of the laser light within each such beam line **22, 23** is not necessarily equal in accordance with the transmission, versus the reflection, characteristics of beamsplitter **30**. Normally, and in accordance with the requirement for light power in each of the beam lines **22, 23**, about 10% of the light **20** goes into beam line **22** and about 90% goes into beam line **23**.

The laser light pulses within beam line **22** are reflected at mirror **31** and again in prism **32** to impinge upon second beamsplitter **33**. The prism **32** may be moved a variable distance, VD_1, from both mirror **31** and beamsplitter **33** in order to induce a variable delay in the time of arrival of the laser light pulses at beamsplitter **33** and at subsequent points.

The beam line **22** is split by second beamsplitter **33** into beam lines **24** and **25**. As with the beamsplitting performed by first beamsplitter **30**, the light energy within each of beam lines **24, 25** need not be equal in accordance with the reflectivity, and transmission, characteristics of beamsplitter **33**. Normally almost all of the light within beam line **22**, about 99%, goes into beam line **24** and the remainder of the light, about 1%, goes into beam line **25**.

The laser light pulses in beam line **24** are transmitted through light transparent window **41** of high-vacuum assembly **40** to illuminate photocathode **42**. The window **41** is normally clear optical quartz. The high-vacuum assembly **40** maintains photocathode **42**, and anode **43**, in a high-vacuum at least less than 10^{-6} torr and, typically about 10^{-9} to about 10^{-10} torr. One such high-vacuum assembly suitable to contain the preferred configuration, and spacing, of photocathode **42** and anode **43** (discussed hereinafter) is manufactured by Huntington Mechanical Laboratories, 1400 Stierlin Road, Mountainview, Calif. 94043. Other high-vacuum chambers of other manufacturers are equally suitably adaptable to the purposes of the present invention.

The photocathode **42** and anode **43** each have a preferred configuration, a preferred separation, and are each preferably constructed of certain materials. The configuration and separation of the photocathode **42** and anode **43** is a function of the desired shaping of the electron beam between such photocathode **42** and anode **43**, and the magnitude of the high voltage that exists between such photocathode **42** and anode **43**. One preferred program for the calculation of the geometries, and separations, of both photocathode **42** and anode **43** is available from Stanford University as SLAC Electron Optics Program Vector POT./PLOTFILE version of July 1979. That computer program is directed to the calculation of the contours of a spherical anode that is used within an electron gun. It is publicly available from the Linear Accelerator program of Stanford University.

A preferred configuration and separation calculated by the SLAC Electron Optics Program for the photocathode **42** and anode **43** is shown in cross-sectional plan view in FIG. **2**. The grid electrode **44** and the focusing plates **45** are also shown.

Each of the photocathode **42**, anode **43**, grid electrode **44** and focusing plates **45** exhibit substantial circular and radial symmetry about an imaginary line of focus **50**. The only substantial deviation from circular and radial symmetry is evidenced by the small front surface, oriented in the direction toward photocathode **42**, of anode **43**. That planar surface is typically angled at 45° relative to line of focus **50** and relative to x-ray pulses **10** (to be discussed), as is best shown in FIG. **1**.

The distance X, or diameter of the photocathode, is typically about 1.75 centimeters (0.69 inches). The grid electrode **44**, preferably in the shape of an annular ring having the indicated cross section and located in a position surrounding the photocathode **42**, has a diameter Y of approximately 5.08 centimeters (2 inches). Its central aperture is approximately 1.78 centimeters (0.7 inches) in diameter, which is sufficient to tightly accommodate the 1.75 centimeter (0.69 inch) diameter of photocathode **42**. The front surface of anode **43**, which is typically about 0.254 centimeters (0.1 inches) in diameter, is nominally located at distance Z=about 1.65 centimeters (0.65 inches) from the surface of photocathode **42**. The major diameter of anode **43** is approximately 0.89 centimeters (0.35 inches).

The one or more focusing plates **45**, which are normally of spheroidal contour with a central aperture, are located approximately half way between cathode **42** and anode **43**, or about 0.82 centimeters (0.32 inches) from either. The focusing plates **45** are typically of hemispherical contour. The configurations, and separations, of photocathode **42**, anode **43**, and focusing plates **45** is directed to sharply focusing an electron beam to a minimum size point on the surface of anode **43** when an approximate 100 kilovolts electrical potential is applied between anode **43** and photocathode **42**.

In accordance with the present invention, the material of photocathode **42** is improved over a similarly-employed photocathode reported in the article "Practical laser-activated photoemissive electron source" by Lee, et al., appearing in *Rev. Sci. Instrum.*, Vol. 56, No. 4: pp. 560–562 (April 1985). Lee, et al. describe a cesium antimonide (Cs_3Sb) photocathode that is alleged to be an improvement on previous gallium arsenide (GaAs) and bialkali photocathode materials. In accordance with the present invention metal is added to a semiconductor material by mixing or, preferably, by depositing through sputtering or by annealing. The metal is preferably tantalum (Ta), copper (Cu), silver (Ag), aluminum (Al) or gold (Au), or oxides or halides of these metals (where possible). The semiconductor is preferably cesium (Cs), cesium antimonide (Cs_3Sb) or gallium arsenide (GaAs). A preferred cathode is constructed from tantalum (Ta) annealed on the surface of nickel (Cs_3Sb). Such a cathode exhibits excellent efficiency in the production of electrons by the photoelectric effect in response to incident green light (λ=193 nm), and exhibits many times, approximately four times (×4) the fifty (50) hour service lifetime reported by Lee, et al.

The anode **43** is preferably made of zirconium (Zr) copper (Cu) or molybdenum (Mo), but other known materials for producing x-ray radiation when bombarded with high-energy electrons are also suitable.

Returning to FIG. **1**, a high voltage electrical potential is provided between anode **43** and photocathode **42** by high voltage power supply **60**. The high voltage of power supply **60** is typically 100 Kv. However, it will be understood that for the purposes of the present invention "high voltage" is any accelerating potential that is suitable for speeding up the electrons in a beam of a cathode ray tube.

In accordance with the principles of the invention for the production of time-resolved x-ray pulses, the nominal 100 Kv voltage of high voltage power supply **60** is not necessarily continually applied between photocathode **42** and anode **43**. Rather, such high voltage may be gated in the circuit including photocathode **42** and anode **43** by action of semiconductor switch device **70**.

It is not required in order to produce time-resolved x-ray pulses that the high voltage power supply **60** should be gated by semiconductor switch device **70**. It is sufficient only that the laser light, and the resulting photoemission of electrons should be pulsed. Moreover, it is not a trivial matter to switch 100 Kv in a few picoseconds, and undesirable arcing may occur between photocathode **42** and anode **43** if the vacuum is not 10^{-9} torr or less, The reason that the high voltage is desirably switched, despite the care that must be given to this procedure, is to better permit the close spatial proximity of photocathode **42** and anode **43**, and the effective acceleration of the emitted electrons in bunches, or packets, i.e., in pulses. Particularly if photocathode **42** and anode **43** are at great separation (undesirably allowing the electrons to disperse during their flight from the photocathode to the anode), it will be recognized by a practitioner of electron gun design that it may not be necessary or worthwhile to switch the high voltage.

The semiconductor switch device **70** is preferably made from heavily P^+ doped silicon. It is typically about 0.1 mm depth×about 3 mm width×about 5 mm length. It may be particularly constructed from a $LiTaO_3$ crystal doped with 2.24% Cu as taught in the article OPTICAL GENERATION OF INTENSE PICOSECOND ELECTRICAL PULSES by Auston, et al. appearing in *Appl. Phys. Lett.* Volume 20, No. 10: pp. 398–399 (May 15, 1972). The copper (Cu) impurities have a strong absorption at 1.06 μm.

The beam line **25** of laser light pulses from laser **21** is reflected in two mirrors **34**, which may be jointly located at a variable distance VD_3 from beamsplitter **33** and from semiconductor switch **70**, so as to impinge upon semiconductor switch **70**. A prism may alternatively be used in substitution for the two mirrors **34**. Each laser light pulse striking the semiconductor switch **70** generates a macroscopic polarization in such switch resultant from the difference in dipole moment between the ground and excited states of the absorbing Cu^{++} impurities. The semiconductor switch **70** will be turned on, conducting the nominal 100 Kv

high voltage from power supply **60** to be applied between photocathode **42** and anode **43**, during the duration of each laser pulse (nominally 20–50 psec in duration). At other times the semiconductor switch **70** will be turned off and the high voltage from high voltage power supply **60** will not be applied between photocathode **42** and anode **43**. The switching action of the preferred semiconductor switch **70** is exceptionally fast, on the order of 2 psec or less.

Because lasers can produce light pulses of femtoseconds duration, and because the switching time of the laser-light-activated semiconductor switch that switches the high voltage is on the order of a few picoseconds or less, the principles of the present invention are applicable to producing x-ray pulses of even shorter than 20 picoseconds duration. The shape and separation of the photocathode and the anode must, however, be precisely controlled in order to prevent electron beam dispersion, and resultant lengthening of the x-ray pulses.

It is not essential that a laser-light-activated semiconductor switch be used to switch the application of the high voltage supplied by high voltage power supply **60** between the photocathode **42** and anode **43**. For example, a magnetron may alternatively be used. Such a magnetron would normally be triggered in its switching action by an electrical circuit that is sensitive to the laser light pulses on beam line **25**. Such circuits, and magnetrons, are commonly understood but are deemed less suitable, and slower, than the preferred semiconductor switch. If a magnetron is used, it may be considered to occupy the location in FIG. **1** that is identified by numeral **70**.

Continuing in FIG. **1**, a grid electrode **44** voltage biased by intermediate voltage power supply **61** may be used to improve the bunching of electrons emitted from photocathode **42**. As may best be observed in FIG. **2**, the grid electrode **44** is positioned surrounding the photocathode **42**. The focusing electrode(s) **45** are typically spaced at a separation of 0.82 centimeters (0.32 inches) from each of the photocathode **42** and anode **43**. The grid electrode **44** is negatively biased relative to photocathode **42** by first intermediate voltage power supply **61**, nominally 3 Kv. The focusing plates **45** are biased relative to photocathode **42** by second intermediate voltage power supply **62**, nominally also 3 Kv. Both the first intermediate voltage power supply **61** and the second intermediate voltage power supply **62** may exhibit a range of voltages, typically 2–8 Kv. It is normally preferred that the voltage of second intermediate voltage power supply **62**, and the voltage on focusing plates **45**, should be equal to or greater than the voltage of first intermediate voltage power supply **61**, and the voltage on grid electrode **44**.

It may be noted that the voltage bias, and the electric field within the vacuum assembly **40**, that is created by the first intermediate voltage power supply **61** is of an opposite polarity to the voltage, and electric field, created by the high voltage power supply **60**. The first intermediate voltage power supply **61** could optionally be switched off, such as by an oppositely phased counterpart switch to semiconductor switch **70**, at the same time that high voltage power supply **60** is switched on. However, this additional switching is not necessary because the electric field created by first intermediate voltage power supply **61** is insignificant in comparison to the electric field created by high voltage power supply **60**.

Certain additional structure is usefully attached to high vacuum assembly **40** in order to support the renewal of photocathode **42**. The photocathode **42**, preferably made of tantalum-surfaced cesium antimonide (Ta on Cs_3Sb), is subject to having its surface ablated by the high intensity laser light impingent upon it from beam line **24**. It periodically needs renewal, typically after greater than 200 hours of use at a higher, 0.66%, duty cycle. In order to do so, an x-ray tube isolation valve **80** is opened. The photocathode **42** is withdrawn into the area under deposition monitoring view port **81** by use of a rotary-translation feedthrough, or transfer device, **82**. The distal, or operative, end of rotary translation feedthrough device **82** comprises a cathode holder **83**. This cathode holder **83** is moved in position while the x-ray tube isolation valve **80** is open so as to engage photocathode **42** and move it to position under deposition monitoring view port **81**. At a later time the cathode holder **83**, and the rotary-translation feedthrough device **82**, is used to restore photocathode **42** to its normal, operative, position as illustrated.

When the photocathode **42** is positioned under the deposition monitoring view port **81** it is supplied with fresh cesium from cesium dispenser **84** and with fresh antimony from antimony dispenser **85**. This deposition is normally performed by sputtering in a high vacuum. At the conclusion of the deposition the surface of photocathode **42** is substantially renewed, and the photocathode **42** may be redeployed for a further period of producing copious electrons by the photoelectric effect. By a slightly differing mechanical arrangement (as illustrated) two cathodes may be employed, with one in use while the other is being resurfaced or held in reserve. The rapidity of cathode renewal and substitution is generally of greater importance when the x-ray source **1** is used in a production, as opposed to a research, environment.

The x-ray pulses **10** that are produced at anode **43** exit the high-vacuum assembly **40** through an x-ray transparent window **46** that is typically made of beryllium (Be).

The x-ray pulses **10** may optionally be gated in their path to scattering sample **2** by an x-ray gating device **90**. Such a device may be, for example, an apertured plate, or disk, **91** that is driven by a motor **92**. The apertured disk **91** is made of a material that is substantially opaque to x-rays, for example lead (Pb). The apertures are transparent to x-rays. The normal rotational speed of apertured disk **91**, which is typically several hundred revolutions per minute, is normally not sufficient so as to gate the passage of an x-ray pulse **10**, essentially traveling at the speed of light, between the anode **43** and the scattering sample **2** when such pulse is only 20–50 picoseconds (6–10 millimeters at the speed of light) in length.

The gating performed by the apertures within the rotating apertured disk **91** can, however, be phased so that such rotating apertured disk **91** serves to truncate either the beginning, or the end, of a time-resolved x-ray pulse. Additionally, it should be understood that the time-resolved x-ray source **1** in accordance with the present invention need not operate exclusively to produce ultrashort, picosecond duration, x-ray pulses. In the event that the x-ray production is continuous, or is produced in pulses of typically millisecond time duration, the x-ray gating assembly **90** may usefully serve to gate the application of x-ray pulses **10** to scattering sample **2**.

The preferred material, and thickness, of the rotating apertured disk **91** is dependent, as is well in the art, on the energy level of the x-ray pulses **10** which are intended to be gated. The "opaque" and "transparent" regions of the disk **91** may substantially block or pass the x-rays **10**, or may attenuate such x-rays **10** to a variable degree. Normally the optional x-ray gating assembly **90** is not employed, but, if it is employed, it may serve as a useful secondary means of

controlling, and gating, both the timing and the intensity application of x-ray radiation to an x-ray target object such as scattering sample **2**.

In operation of the x-ray source **1** for the production of continuous x-ray radiation, a continuous laser light beam produced by a laser **21** continuously impinges upon a photocathode **42** that is located in a high vacuum in order to cause such photocathode **42** to continuously emit numerous electrons by the photoelectric effect. The emitted electrons are continuously accelerated, and focused, in a continuous high voltage electric field that is produced by high voltage power supply **60**, so as to continuously strike anode **43** at a small focal spot, typically 0.5 mm or less in diameter. The resulting x-rays are used to illuminate a scattering sample **2**, or other x-ray target.

Use of the x-ray source **1** in the production of time-resolved x-rays proceeds equivalently. In this use a pulsed laser **21** produces time-resolved pulses of high intensity laser light. Each such laser light pulse causes the photoemission of electrons from photocathode **42**. The emitted electrons are preferably maintained in a spatial region that is proximate to photocathode **42**, and separated from anode **43**, by use of a negatively-biased grid electrode **44**. Upon such time as a cloud of electrons has been accumulated in the region between the photocathode **42** and grid electrode **44** within the high vacuum chamber **40**, a laser light pulse turns on the semiconductor switch **70** in order to apply the high voltage from high voltage power supply **60** to photocathode **42** and anode **43**. Even though the first intermediate voltage power supply **61** is not normally turned off, the accumulated electrons are accelerated from photocathode **42** through electrode **44** to anode **43** as a tightly focused electron beam, or beam packet. The beam packet of electrons strikes the anode **43**, or any other electron target that is substituted in their line of flight, with high energy, producing a pulse of x-ray radiation. This pulse of x-ray radiation, which is optionally gated and/or attenuated by a further x-ray gating means **90**, impinges upon the scattering sample **2**, or other x-ray target.

In accordance with still another aspect of the present invention, the scattering sample **2** is energized, including for the initiation and/or maintenance of a molecular reaction therein, by the same laser light pulses that give rise to the x-ray pulses.

This light energization of scattering sample **2** is accomplished by directing the laser light pulses on beam line **23** with mirror **35**, prism **36**, and mirror **37** to impinge on scattering sample **2**. The prism **36** may be moved a variable distance, VD_2, relative to mirrors **35**, **37** in order to adjust the time at which laser light pulse line **23** is incident upon scattering sample **2** relative to the time at which x-ray pulses **10** are received at the same scattering sample **2**. Due to the relatively slow passage of the electron beam packet between photocathode **42** and anode **43** within high vacuum assembly **40**, the time of incidence of the laser pulses on beam line **23** at scattering sample **2** may be readily adjusted to be either earlier than, coincident with, or later than, the time of arrival of the x-ray pulses **10** at the same scattering sample **2**. The present invention thus contemplates not only the economical and compact production of ultrashort time-resolved x-ray pulses, but also the convenient initiation and energization of molecular reactions that may usefully be examined with such ultrashort time-resolved x-ray pulses.

The x-ray source **1** is aligned. A preferred alignment of time-resolved x-ray source **1** enables the high voltage to be applied between photocathode **42** and anode **43** for the duration of the photoemission from photocathode **42**. If the high voltage power supply **60** is not to be switched by device **70**, then adjustment of delay VD_3 makes it a simple matter to trigger a photodiode, or other light sensor device, to turn on high voltage power supply **60**. This turn on typically transpires about 5 nsec before the arrival of the light pulse at photocathode **42** via beam line **24**. In other words, beam line **25** is about 1.5 meter (5 feet) shorter to the point where it is sensed than is beam line **24** to the photocathode **42**. The power supply **60** is typically turned off after a predetermined time delay, normally of several microseconds.

If the high voltage from high voltage power supply **60** is to be switched by semiconductor switch device **70** to photocathode **42** and anode **43** simultaneously that the laser light pulse arrives at photocathode **42** via beam line **24**, then a more exacting alignment of x-ray source **1** is necessary. In order to conduct this alignment, both the semiconductor switch device **70** and the photocathode **42** are normally temporarily replaced with photodiodes. The arrival of the laser pulse at the two points is made to be coincident, to the limits of observational accuracy and jitter, by observing the coincidence of both photodiodes' signal outputs on an oscilloscope, and by adjusting the length beam line path **25**. The shortening or lengthening of beam line path **25** is at the scale of 1 psec~0.3 mm.

The actual physical beam line paths **24** and **25** are obviously not spatially laid out as illustrated in FIG. **1**, which is diagrammatic only. It is within the ability of a user of a laser to adjust the length of an optical path, and to correlate in time events occurring on two such paths.

It may be useful to temporally spread out, or dispense the arrival of the laser pulse on beam line **25** at semiconductor switch device **70**. In such a case a solution of bromobenzene in a glass tube may be placed in the beam line **25**.

It should be understood that it is not absolutely necessary for the laser light pulse that activates the semiconductor switch to be synchronized (temporally coincident) with the laser light pulse that causes the photoemission. Photoemission and electron accumulation can precede acceleration and focusing of the electron beam. Especially if a very intense x-ray pulse is preferred to a very short one, it may be advantageous to accrue electrons before switching on the high voltage.

In accordance with the preceding discussion, certain adaptations and alterations of the invention will suggest themselves to practitioners in the art of designing x-ray sources. The temporal phasing between the various activities performed in and by the x-ray source in accordance with the present invention is widely variable. There need not even be a one-to-one correspondence between each such activity. For example, the accumulation of electrons in the region between electrode **45** and photocathode **42** could transpire for several laser light pulses. There need not be just one semiconductor switch **70**. Another such semiconductor switch, alternately phased, could be applied to the first intermediate voltage power supply **61**. The switching of the high voltage power supply need not be by a semiconductor switch, but could, alternatively, be by an appropriately time-synchronized magnetron switch. Indeed, there may be no switching of the high voltage power supply at all. There need not be just one laser used in the x-ray source. Multiple lasers, appropriately phased and adapted in frequency and intensity relative to the separate tasks performed, could be employed.

The x-ray source in accordance with the present invention is adaptable to a wide range of (i) x-ray frequencies, (ii)

x-ray intensities, and (iii) x-ray pulse lengths from continuous to picosecond and shorter duration. A single x-ray source is, however, normally inefficient over an operational range that is simultaneously broad in all of the many variables. This inefficiency results from a requirement for optimizing the configurations, and spacing, of the photocathode 42 and anode 43 that cannot simultaneously be satisfied for a great range of many differential operational conditions. However, x-ray sources in accordance with the present invention can readily be constructed to efficiently provide a broad range of x-ray frequencies, intensities, and pulse durations that are useful to diverse x-ray spectroscopy and x-ray lithography activities, and to other activities requiring time-resolved x-rays.

One embodiment of the invention is a pulsed x-ray source particularly directed for use in x-ray lithography. Using a tantalum film as the photocathode material and 266 nm picosecond pulses from a pulsed mode locked Nd:YAG laser, electron bunches with a charge of 3 nC per pulse have been generated. These electron pulses are accelerated and focused onto a copper anode to produce x-ray pulses with time width of a 20 ps and a brightness of 6.2×10^6 cm^{-2} sr^{-1} at the Ka wavelength (1.54 Å).

The use of deep ultraviolet, 193 nm, light combined with the use of pure metal photocathodes is a very efficient as a source of electrons, and hence of x-rays. The advantages of a metal photocathode include a quantum efficiency of the order of approximately 10^{-3}, a guaranteed long life at a moderate vacuum, and reliability over hundreds of hours of use without incurring any observable deterioration or variation in performance. In addition, the use of pulsed radiation makes possible the generation of a very high peak photocurrent. High power x-ray pulses, with an average power of 5 Mw/cm^2 and a peak power of 20 Mw/cm^2, can be emitted from surface areas as large as 10–20 cm^2 and larger.

The wide area x-ray source in accordance with the present invention can accordingly be used in a simple close-contact arrangement of the X-ray mask and the resists—without the need of focusing! Because of the high intensity, short, X-ray pulses produced, the chemical amplification process in the resist is increased—resulting in a much higher yield.

In its wide-area embodiment the present invention is a compact, high intensity, inexpensive, reliable, tunable pulsed x-ray (PXR) source providing reproducible x-ray pulses with an intensity, up to approximately 20 mW/cm^2, that is comparable to that of other sources, such as impact tubes and laser-driven plasma-based sources.

The wide-area x-ray source consists of a simple plane diode, as illustrated in FIG. 3. The photocathode is made from a pure metal having a low work function, such as, for example, Ta, Sm or Ni. The metal photocathode is irradiated with laser pulses, preferably 193 nm laser pulses. Each electron bunch that is emitted in response to a corresponding laser pulse is accelerated to, and is focused onto, the anode by means of high electric fields. (The focusing is obviously over a much larger area, normally ranging to a circular area of up to 20 cm^2, than is the focusing occurring in the previous embodiment of FIGS. 1 and 2—which previous embodiment may be directed to producing a point x-ray source. Nonetheless, the electron bunch of the wide-area source is spoken of as being "focused" into a wavefront because its dispersion, and its spatial extent (even if over a relatively extended area) are obviously managed and controlled.)

The anode is a thin metal foil which emits x-rays in the forward direction under electron impact. Note that this is opposite to the previous embodiment of FIGS. 1 and 2. For this reason the wide area source is sometimes described as "through-path-transmitting", meaning that the electron and the x-ray radiation are along the same axis, and in substantially the same direction. Low Z number metals are preferred for the anode because they emit x-rays at longer wavelengths, such as the characteristic radiation of Al at 0.83 nm.

In order to evaluate the output x-ray power of the wide-area X-ray source in accordance with the present invention the main characteristics of its diode construction should be considered. In the pulsed mode of operation, when the transit time t_t of the electrons across the diode is less than the laser pulse duration t_p, the peak current density is given by:

$$J=q/t_p$$

where q is the available charge on the cathode. The maximum value of q per unit area is given by

$$q=E_o\times V/d$$

where V is the applied voltage and d is the separation of the anode and cathode.

If we assume a cathode area of 1 cm^2, d=1 cm and V=200 KV, the transient regime takes place for laser pulses shorter than 100 ps while the available electrons per unit area of the cathode are 1.1×10^{11} electrons/cm^2. For a photo-cathode quantum efficiency of 10^{-4} a laser energy of 1.0 mJ/cm^2 per pulse in required. Assuming an Aluminum anode, the efficiency of the Ka line production will be of the order of 10^{-3}, which means that 1.6 $\mu J/cm^2$ of x-rays in the forward direction will be produced per pulse.

With a quite reasonable 50% transmission of the anode and substrate, a 0.8 $\mu j/cm^2$ energy density per pulse is produced on the working surface. This requirement for laser light illumination should be compared with the with certain UV radiation generating lasers (193 nm is discussed below) currently available in the U.S.A. market (circa 1991), which lasers operate at a repetition rate up to 300 Hz. Thus, the average output is 240 $\mu j/cm^2$. Therefore, a pulsed laser system using an ArF amplifier with 20 mJ/pulse will be able to irradiate 20 cm^2 of mask area simultaneously.

The production of electrons may be increased by a factor of 10 or more by using 193 nm wavelength irradiation because quantum efficiency is related to the laser energy by

$$n=A_{(z)}(h\nu-W_o)^2$$

where $A_{(z)}$ is a constant characteristic of the metal, hv is the laser photon energy and W_o is the work function of the metal. This equation shows that the electron production quantum yield increases with the square of difference between the photon energy and work function. An increase by at least a factor of 10 is realized by use of 193 nm laser pulses.

In order to take full advantage of the enhanced quantum efficiency as the work function energy is exceeded, a new and powerful source of 193 nm photons is required. In accordance with the present invention, a new and powerful 193 nm x-ray source is based upon the use of an argon-fluoride laser as an amplifier. It is constructed as follows: A Nd:YLF laser emitting laser light at 1057 nm is up-converted in frequency to generate pulses at 527 nm, 265 nm and 211 nm wavelengths at a 1 Khz repetition rate. This manner of frequency conversion is known in the art.

The 527 nm beam is next used to pump a dye laser which emits 728 nm light. The next step involves the frequency

mixing, in a Barium Borate (BBO) crystal, of the 728 nm dye laser pulse with the 263 nm fourth harmonic of the frequency-converted primary laser pulse so as to generate a "seed" pulse at 193 nm wavelength. This part has not been done previously. Calculations show that there is a phase matching angle, and because the BBO crystal transmits about 50% at 192 nm, a strong seed pulse is generated for subsequent amplification.

While the common argon-fluoride laser has not been used extensively as an amplifier at 193 nm, other excimer lasers, such as the KrF laser at 248 nm, have been used with very satisfactory results for a long time.

The complete wide-area x-ray source in accordance with the present invention, as described, is inexpensive. The main components of the system are currently available in the U.S.A. scientific market. The development of the 192 nm "seed" pulse is new, but straightforward. The 300 Hz rate is limited only by the ArF amplifier. However, new excimer amplifiers—such as one from Lambda Physik with a 1 Khz rep-rate—are regularly entering the market. Regenerative amplifiers with YAG and YLF crystals offering repetition rates up to 1 kHz are commercially available now with 1 KHz now, and prototype lasers for laboratory use are available with repetition rates up to 10 Khz. For a complete solid state system, the dye laser/amplifier stage of the present invention can alternatively be replaced with a Ti-sapphire laser.

A table top wide-area x-ray source is thus able to produce x-ray radiation with average intensity in the range of 1 mW/cm^2 over an area of 20 cm^2. The x-ray wavelength most convenient will be in the range of 0.1 nm to 1 nm. If, instead of picosecond pulse, longer 10–20 ns pulses are used then higher average powers, can be generated, i.e., 20–30 mW/cm^2 of x-rays in a 20 cm^2 area and with very little shot to shot variation because of the electron saturation of the diode. The x-ray irradiation area can be increased to 40 cm^2 or more without loss in the per cm^2 flux, by simply increasing the diameter of the amplifier.

Since the x-ray output of the source is of large size a contact mask will be most suitable, as illustrated in FIG. 3. The mask is normally placed tight against the anode at a separation $\leqq 5$ micrometers. One preferred configuration involves the use of a mask and thick absorber. The thickness of the absorber is desirably more than an order of magnitude larger than the resolution limit. The thick absorber improves the contrast of the mask. Additionally, the distance between x-ray plate and the mask must be as small as possible (less than 5 micrometers). The high peak power of the x-ray will be advantageous for resists with chemical amplification since large numbers of electrons are produced in the exposed area within the short duration of the x-ray pulse—thus increasing the chemical amplification.

A laser-induced pulsed wide-area x-ray source in accordance with the present invention typically generates 1–10 mW/cm^2 of x-rays from picosecond duration laser pulses, and 20–40 mW/cm^2 of x-rays from 20 ns, 193 nm pulses. The pulse repetition rate is 300 Hz minimum, 1,000 Hz typical. A table top size induces stable (±15%) x-ray pulses over large irradiation areas. The x-ray pulses are highly reliable, providing trouble free operation for hundred of hours.

In accordance with the preceding explanation, the present invention should be interpreted broadly, in accordance with the following claims, only, and not solely in accordance with that preferred embodiment within which the invention has been taught.

What is claimed is:

1. An x-ray source for producing x-ray illumination over an area of a workpiece semiconductor substrate, the source comprising:

a laser beam generating means for producing a laser light beam having a cross-sectional area substantially as large as the area of the workpiece semiconductor substrate;

a photoelectron emitter means, intercepting the laser light beam over a light intercept area substantially as large as the laser light beam cross-sectional area, for producing electrons by the photoelectric effect over an electron production area substantially as large as the light intercept area;

a high voltage means for generating an electric field for accelerating the produced electrons as an electron beam wavefront over an area substantially as large as the electron production area;

a metal foil, positioned to intercept the electron beam wavefront over substantially its entire area, for producing x-rays over substantially the entire electron intercept area in response thereto;

wherein because the x-rays are produced over substantially the entire electron intercept area, because the electron intercept area is substantially the entire area of the electron beam wavefront, because the area of the electron beam wavefront is substantially as large as the area of light intercept, because the area of light intercept is substantially as large as the laser light beam cross-sectional area, and because the laser light beam cross-sectional area is substantially as large as the area of the workpiece semiconductor substrate, the x-rays are produced over an area that is also substantially as large as the area of the workpiece semiconductor substrate.

2. The x-ray source according to claim 1 wherein the laser beam generating means comprises:

a laser means for producing pulses of laser light that constitute a temporally intermittent laser beam.

3. The x-ray source according to claim 1 comprising:

a high voltage switching means selectively operable to energize the high voltage means for a selected period of time for producing said wavefront of electrons during said period of time.

4. The x-ray source according to claim 3 wherein the laser beam generating means comprises:

a means for producing said laser beam as pulses in synchronization with the energizing of the high voltage means.

5. The x-ray source according to claim 4 wherein the high voltage switching means comprises:

an electrical switch selectively operable to energize the high voltage means in response to and in synchronization with said laser beam pulses.

6. The x-ray source according to claim 1 wherein the spatially extended photoelectron emitter means comprises:

a photocathode;

wherein the spatially extended metal foil comprises:

an anode;

and wherein the high voltage means comprises:

a source of a high voltage potential between the anode and the cathode.

7. The x-ray source according to claim 1 wherein the photoelectron emitter means consists essentially of pure metal having a low work function.

8. The x-ray source according to claim 7 wherein the pure metal having a low work function consists essentially of a metal from the group of Ta, Sm, and Ni.

9. The x-ray source according to claim 1 wherein the metal foil consists essentially of aluminum.

10. The x-ray source according to claim 1 wherein the spatially extended photoelectron emitter means comprises:

a substantially planar photocathode;

and wherein the spatially extended metal foil is substantially planar.

11. The x-ray source according to claim 1 wherein the spatially-extended photoelectron emitter means comprises:

a spatially-extended photocathode consisting essentially of a semiconductor in combination with a metal.

12. The x-ray source according to claim 11 wherein the spatially-extended photocathode's semiconductor is selected from the group consisting essentially of cesium and cesium antimonide and oxides pf cesium and cesium antimonide.

13. The x-ray source according to claim 11 wherein the spatially-extended photocathode's metal is selected from the group consisting of tantalum, copper, silver, aluminum and gold, and oxides of tantalum, copper, silver, and aluminum, and halides of tantalum, copper, silver, and aluminum.

14. The x-ray source according to claim 11 wherein the spatially-extended photocathode spatially-extended photocathode consists essentially of the metal deposited on the surface of the semiconductor.

15. The x-ray source according to claim 11 wherein the spatially-extended photocathode consists essentially of the metal substantially homogeneously mixed in bulk with the semiconductor.

16. The x-ray source according to claim 11 wherein the spatially-extended photocathode's semiconductor comprises:

a substrate;

and wherein the photocathode's metal comprises:

a layer upon the semiconductor substrate.

17. The x-ray source according to claim 16 wherein the spatially-extended photocathode's metal layer is sputtered on the photocathode's semiconductor substrate.

18. The x-ray source according to claim 16 wherein the spatially-extended photocathode's metal layer is annealed to the surface of the photocathode's semiconductor substrate.

19. A method of producing x-ray illumination over an area of a workpiece semiconductor substrate, the method comprising:

illuminating with a laser light beam having a cross-sectional area that is substantially as large as the area of the workpiece semiconductor substrate an area of a photoelectron emitter in order to produce electrons by the photoelectric effect over the photoelectron emitter area;

generating a high voltage electric field in order to accelerate the produced electrons as a wavefront of electrons, the wavefront occupying an area substantially as large as the photoelectron emitter area from whence the electrons arose; and

intercepting the wavefront of electrons with an area of metal substantially as large as the wavefront in order to produce x-ray radiation over an area of intercept substantially as large as the wavefront of electrons;

wherein the cross-sectional area of the laser light beam, the photoemitter area, the area of the wavefront of electrons, the area of intercept, and the x-ray produced radiation are all substantially the same size, and are all substantially as large as the area of the workpiece semiconductor substrate.

20. The method of producing x-ray illumination over a spatially extended area according to claim 19 wherein the illuminating comprises:

illuminating with the laser light the spatially extended area of a spatially-extended photocathode consisting essentially of a semiconductor in combination with a metal.

21. The method of producing x-ray illumination over a spatially extended area according to claim 20 wherein the illuminating of the spatially-extended photocathode consisting essentially of a semiconductor in combination with a metal serves to illuminate a semiconductor selected from the group consisting essentially of cesium and cesium antimonide and oxides of cesium and cesium antimonide.

22. The method of producing x-ray illumination over a spatially extended area according to claim 20 wherein the illuminating of the spatially-extended photocathode consisting essentially of a semiconductor in combination with a metal serves to illuminate a metal selected from the group consisting of tantalum, copper, silver, aluminum and gold, and oxides of tantalum, copper, silver, and aluminum, and halides of tantalum, copper, silver, and aluminum.

23. The method of producing x-ray illumination over a spatially extended area according to claim 20 wherein the illuminating is of the spatially-extended photocathode consisting essentially of the metal deposited on the surface of the semiconductor.

24. The method of producing x-ray illumination over a spatially extended area according to claim 20 wherein the illuminating is of the spatially-extended photocathode consisting essentially of the metal substantially homogeneously mixed in bulk with the semiconductor.

25. A method of producing x-ray illumination over a area of a workpiece semiconductor substrate, the method comprising:

illuminating with a laser light beam having a cross-sectional area that is substantially the same as an area of the workpiece semiconductor substrate an area, substantially the same size as is the laser light beam cross-sectional area, of a photocathode consisting essentially of a semiconductor in combination with a metal in order to produce electrons by the photoelectric effect over a photoelectron emission area substantially the same size as are both the laser light beam cross-sectional area and the workpiece semiconductor substrate;

generating a high voltage electric field in order to accelerate the produced electrons as a wavefront of electrons, the wavefront occupying an area substantially the same size as the photoelectron emission area from whence the electrons arose; and

intercepting the wavefront of electrons with metal in order to produce x-ray radiation over an area of intercept that is substantially the same size as is the wavefront;

wherein the cross-sectional area of the laser light beam, the photoelectron emission area, the area of the wavefront of electrons, and the area of intercept are all substantially the same size, and are all substantially the same size as the workpiece semiconductor substrate.

26. An x-ray source for producing x-ray illumination over a area of a workpiece semiconductor substrate, the source comprising:

a laser beam generating means for producing a laser light beam having a cross-sectional area that is as large as the area of the workpiece semiconductor substrate;

a semiconductor;

a metal layer on the semiconductor, which metal layer emits electrons by the photoelectric effect in response to illumination by light, intercepting the laser light beam over a light intercept area as large as the laser light beam cross-sectional area, for producing electrons by the photoelectric effect over an electron production area as large as the light intercept area;

a high voltage means for generating an electric field for accelerating the produced electrons as an electron beam wavefront over an area as large as the electron production area;

a metal foil, positioned to intercept the electron beam wavefront, for producing x-rays over an electron intercept area as large as the electron beam wavefront in response thereto;

wherein because the x-rays are produced over the entire electron intercept area, because the electron intercept area is as large as the electron beam wavefront, because the area of the electron beam wavefront is as large as the area of light intercept, because the area of light intercept is as large as the laser light beam cross-sectional area, and because the laser light beam cross-sectional area is as large as the area of the workpiece semiconductor substrate, the x-rays are produced over an area that is also as large as the area of the workpiece semiconductor substrate.

27. An x-ray source for producing x-ray illumination over a area of a workpiece semiconductor substrate, the source comprising:

a laser beam generating means for producing a laser light beam;

a photoelectron emitter means, intercepting the laser light beam in order to produce by the photoelectric effect electrons over an electron production area that is as large as is the area of the workpiece semiconductor substrate;

a high voltage means for generating an electric field in order to accelerate the produced electrons as an electron beam wavefront having an area that is as large as is the area over which the electrons were produced, namely an area that is yet again as large as is the area of the workpiece semiconductor substrate;

a metal foil for intercepting the entire electron beam wavefront in order to produce x-rays over an area of electron intercept that is as large as is the area of the electron beam wavefront, namely an area that is still yet again as large as is the area of the workpiece semiconductor substrate.

28. A method of producing x-ray illumination over a area of a workpiece semiconductor substrate, the method comprising:

producing a laser light beam with a laser;

intercepting the laser light beam with a photoelectron emitter in order to produce by the photoelectric effect electrons over an electron production area that is as large as is the area of the workpiece semiconductor substrate;

generating with a high voltage source an electric field in order to accelerate the produced electrons as an electron beam wavefront having an area that is as large as is the area over which the electrons were produced, namely an area that is as large as is the area of the workpiece semiconductor substrate; and

intercepting with a metal foil the entire electron beam wavefront in order to produce x-rays over an area of electron intercept that is as large as is the area of the electron beam wavefront, namely an area that is as large as is the area of the workpiece semiconductor substrate.

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